QCD effects in B-decays: Lecture 3

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Outline of these lectures

1. Heavy quark physics
    - Heavy-quark spin and flavor symmetry
        - Spectroscopic implications
    - Heavy Quark Effective Theory
        - V_{cb} from exclusive semileptonic decay
2. Inclusive B-decays
    - Operator Product Expansion
    - Determination of V_{ub}, V_{cb} from semileptonic decays
    - Radiative decays: test of FCNC interactions
    - Heavy hadron lifetimes
3. Exclusive hadronic B-decays
    - Factorization, Soft Collinear Effective Theory

Exclusive *b*-decays

- An extremely rich field:
  - $m_b \gg \Lambda_{QCD}$: **MANY** decay channels!
- Classification (*B* stands for B, B_s , Λ_b)
  - Leptonic: $B \to l^+ l^-$, $B \to l\nu$
  - Semi-leptonic: $B \to H\, l\nu$
  - Radiative: $B \to H\, \gamma$, $B \to H\, l^+ l^-$
  - Hadronic: $M = \pi, K, \rho, \eta, \ldots$
    - charmless: $B \to M_1\, M_2, \ldots$
    - D-modes: $B \to D\, M, \ldots$
    - charmonium modes: $B \to J/\psi\, M, \ldots$
    - baryonic modes: $B \to p\, p$, $B \to \Lambda_c\, p$, ...

PDG ⇒ BDG

(from Z. Ligeti)

B^+ DECAY MODES

B^- modes are charge conjugates of the modes below. Modes which do not identify the charge state of the B are listed in the $B^\pm/B^0$ ADMIXTURE section.

The branching fractions listed below assume 50% $B^0 \overline{B}^0$ and 50% $B^+ B^-$ production at the $\Upsilon(4S)$. We have attempted to bring older measurements up to date by rescaling their assumed $\Upsilon(4S)$ production ratio to 50:50 and their assumed D, D_s, D^*, and ψ branching ratios to current values whenever this would affect our averages and best limits significantly.

Indentation is used to indicate a subchannel of a previous reaction. All resonant subchannels have been corrected for resonance branching fractions to the final state so the sum of the subchannel branching fractions can exceed that of the final state.

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Semileptonic and leptonic modes			
Γ_1	$\ell^+ \nu_\ell$ anything	[a]	(10.9 ± 0.4) %	
Γ_2	$\overline{D}^0 \ell^+ \nu_\ell$	[a]	(2.15 ± 0.22) %	
Γ_3	$\overline{D}^*(2007)^0 \ell^+ \nu_\ell$	[a]	(6.5 ± 0.5) %	
Γ_4	$\overline{D}_1(2420)^0 \ell^+ \nu_\ell$		(5.6 ± 1.6) $\times 10^{-3}$	
Γ_5	$\overline{D}^*_2(2460)^0 \ell^+ \nu_\ell$		< 8 $\times 10^{-3}$	CL=90%
Γ_6	$D^- \pi^+ \ell^+ \nu_\ell$		(5.3 ± 1.0) $\times 10^{-3}$	
Γ_7	$D^{*-} \pi^+ \ell^+ \nu_\ell$		(6.4 ± 1.5) $\times 10^{-3}$	
Γ_8	$\pi^0 \ell^+ \nu_\ell$		(7.4 ± 1.1) $\times 10^{-5}$	
Γ_9	$\pi^0 e^+ \nu_e$			
Γ_{10}	$\eta \ell^+ \nu_\ell$		(8 ± 4) $\times 10^{-5}$	
Γ_{11}	$\omega \ell^+ \nu_\ell$	[a]	(1.3 ± 0.6) $\times 10^{-4}$	
Γ_{12}	$\omega \mu^+ \nu_\mu$			
Γ_{13}	$\rho^0 \ell^+ \nu_\ell$	[a]	(1.24 ± 0.23) $\times 10^{-4}$	
Γ_{14}	$p \overline{p} e^+ \nu_e$		< 5.2 $\times 10^{-3}$	CL=90%
Γ_{15}	$e^+ \nu_e$		< 1.5 $\times 10^{-5}$	CL=90%
Γ_{16}	$\mu^+ \nu_\mu$		< 6.6 $\times 10^{-6}$	CL=90%
Γ_{17}	$\tau^+ \nu_\tau$		< 2.6 $\times 10^{-4}$	CL=90%
Γ_{18}	$e^+ \nu_e \gamma$		< 2.0 $\times 10^{-4}$	CL=90%
Γ_{19}	$\mu^+ \nu_\mu \gamma$		< 5.2 $\times 10^{-5}$	CL=90%

D, D^*, or D_s modes

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_{31}	$\overline{D}^0 \pi^+$		(4.92 ± 0.20) $\times 10^{-3}$	
Γ_{32}	$D_{CP(+1)} \pi^+$	[b]	(4.0 ± 0.8) $\times 10^{-3}$	
Γ_{33}	$D_{CP(-1)} \pi^+$	[b]	(3.6 ± 0.8) $\times 10^{-3}$	
Γ_{34}	$\overline{D}^0 \rho^+$		(1.34 ± 0.18) %	
Γ_{35}	$\overline{D}^0 K^+$		(4.08 ± 0.24) $\times 10^{-4}$	
Γ_{36}	$D_{CP(+1)} K^+$	[b]	(3.7 ± 0.6) $\times 10^{-4}$	
Γ_{37}	$D_{CP(-1)} K^+$	[b]	(3.5 ± 0.5) $\times 10^{-4}$	
Γ_{38}	$[K^- \pi^+]_D K^+$	[c]		
Γ_{39}	$[K^+ \pi^-]_D K^+$	[c]		
Γ_{40}	$[K^- \pi^+]_D K^*(892)^+$	[c]		
Γ_{41}	$[K^+ \pi^-]_D K^*(892)^+$	[c]		
Γ_{42}	$[K^- \pi^+]_D \pi^+$	[c]	(1.7 ± 0.5) $\times 10^{-5}$	
Γ_{43}	$[\pi^+ \pi^- \pi^0]_D K^-$		(5.5 ± 1.2) $\times 10^{-6}$	
Γ_{44}	$\overline{D}^0 K^*(892)^+$		(6.3 ± 0.8) $\times 10^{-4}$	
Γ_{45}	$D_{CP(-1)} K^*(892)^+$	[b]	(2.0 ± 0.9) $\times 10^{-4}$	
Γ_{46}	$D_{CP(+1)} K^*(892)^+$	[b]	(6.2 ± 1.5) $\times 10^{-4}$	
Γ_{47}	$\overline{D}^0 K^+ \overline{K}^0$		(5.5 ± 1.6) $\times 10^{-4}$	
Γ_{48}	$\overline{D}^0 K^+ \overline{K}^*(892)^0$		(7.5 ± 1.7) $\times 10^{-4}$	
Γ_{49}	$\overline{D}^0 \pi^+ \pi^+ \pi^-$		(1.1 ± 0.4) %	
Γ_{50}	$\overline{D}^0 \pi^+ \pi^+ \pi^-$ nonresonant		(5 ± 4) $\times 10^{-3}$	
Γ_{51}	$\overline{D}^0 \pi^+ \rho^0$		(4.2 ± 3.0) $\times 10^{-3}$	
Γ_{52}	$\overline{D}^0 a_1(1260)^+$		(4 ± 4) $\times 10^{-3}$	
Γ_{53}	$\overline{D}^0 \omega \pi^+$		(4.1 ± 0.9) $\times 10^{-3}$	
Γ_{54}	$D^*(2010)^- \pi^+ \pi^+$		(1.35 ± 0.22) $\times 10^{-3}$	
Γ_{55}	$D^- \pi^+ \pi^+$		(1.02 ± 0.16) $\times 10^{-3}$	
Γ_{56}	$D^+ K^0$		< 5.0 $\times 10^{-6}$	CL=90%
Γ_{57}	$\overline{D}^*(2007)^0 \pi^+$		(4.6 ± 0.4) $\times 10^{-3}$	
Γ_{58}	$\overline{D}^{*0}_{CP(+1)} \pi^+$	[d]		
Γ_{59}	$D^{*0}_{CP(-1)} \pi^+$	[d]		
Γ_{60}	$\overline{D}^*(2007)^0 \omega \pi^+$		(4.5 ± 1.2) $\times 10^{-3}$	
Γ_{61}	$\overline{D}^*(2007)^0 \rho^+$		(9.8 ± 1.7) $\times 10^{-3}$	
Γ_{62}	$\overline{D}^*(2007)^0 K^+$		(3.7 ± 0.4) $\times 10^{-4}$	
Γ_{63}	$\overline{D}^{*0}_{CP(+1)} K^+$	[d]		
Γ_{64}	$\overline{D}^{*0}_{CP(-1)} K^+$	[d]		
Γ_{65}	$\overline{D}^*(2007)^0 K^*(892)^+$		(8.1 ± 1.4) $\times 10^{-4}$	
Γ_{66}	$\overline{D}^*(2007)^0 K^+ \overline{K}^0$		< 1.06 $\times 10^{-3}$	CL=90%
Γ_{67}	$\overline{D}^*(2007)^0 K^+ K^*(892)^0$		(1.5 ± 0.4) $\times 10^{-3}$	
Γ_{68}	$\overline{D}^*(2007)^0 \pi^+ \pi^+ \pi^-$		(1.03 ± 0.12) %	
Γ_{69}	$\overline{D}^*(2007)^0 a_1(1260)^+$		(1.9 ± 0.5) %	
Γ_{70}	$\overline{D}^*(2007)^0 \pi^- \pi^+ \pi^+ \pi^0$		(1.8 ± 0.4) %	
Γ_{71}	$\overline{D}^{*0} 3\pi^+ 2\pi^-$		(5.7 ± 1.2) $\times 10^{-3}$	

Γ_{72}	$D^*(2010)^+\pi^0$	$<$ 1.7	$\times 10^{-4}$	CL=90%
Γ_{73}	$D^*(2010)^+K^0$	$<$ 9.0	$\times 10^{-6}$	CL=90%
Γ_{74}	$D^*(2010)^-\pi^+\pi^+\pi^0$	(1.5 $\pm$ 0.7)	%	
Γ_{75}	$D^*(2010)^-\pi^+\pi^+\pi^+\pi^-$	(2.6 $\pm$ 0.4)	$\times 10^{-3}$	
Γ_{76}	$\overline{D}{}^*_1(2420)^0\pi^+$	(1.5 $\pm$ 0.6)	$\times 10^{-3}$	S=1.3
Γ_{77}	$\overline{D}_1(2420)^0\pi^+ \times B(\overline{D}{}^0_1 \rightarrow \overline{D}{}^0\pi^+\pi^-)$	(1.9 $^{+0.5}_{-0.6}$)	$\times 10^{-4}$	
Γ_{78}	$\overline{D}{}^*_2(2462)^0\pi^+ \times B(\overline{D}{}^*_2(2462)^0 \rightarrow D^-\pi^+)$	(3.4 $\pm$ 0.8)	$\times 10^{-4}$	
Γ_{79}	$\overline{D}{}^*_0(2308)^0\pi^+ \times B(\overline{D}{}^*_0(2308)^0 \rightarrow D^-\pi^+)$	(6.1 $\pm$ 1.9)	$\times 10^{-4}$	
Γ_{80}	$\overline{D}_1(2421)^0\pi^+ \times B(\overline{D}_1(2421)^0 \rightarrow D^{*-}\pi^+)$	(6.8 $\pm$ 1.5)	$\times 10^{-4}$	
Γ_{81}	$\overline{D}{}^*_2(2462)^0\pi^+ \times B(\overline{D}{}^*_2(2462)^0 \rightarrow D^{*-}\pi^+)$	(1.8 $\pm$ 0.5)	$\times 10^{-4}$	
Γ_{82}	$\overline{D}{}'_1(2427)^0\pi^+ \times B(\overline{D}{}'_1(2427)^0 \rightarrow D^{*-}\pi^+)$	(5.0 $\pm$ 1.2)	$\times 10^{-4}$	
Γ_{83}	$\overline{D}_1(2420)^0\pi^+ \times B(\overline{D}{}^0_1 \rightarrow \overline{D}{}^{*0}\pi^+\pi^-)$	$<$ 6	$\times 10^{-6}$	CL=90%
Γ_{84}	$\overline{D}{}^*_1(2420)^0\rho^+$	$<$ 1.4	$\times 10^{-3}$	CL=90%
Γ_{85}	$\overline{D}{}^*_2(2460)^0\pi^+$	$<$ 1.3	$\times 10^{-3}$	CL=90%
Γ_{86}	$\overline{D}{}^*_2(2460)^0\pi^+ \times B(\overline{D}{}^{*0}_2 \rightarrow \overline{D}{}^{*0}\pi^+\pi^-)$	$<$ 2.2	$\times 10^{-5}$	CL=90%
Γ_{87}	$\overline{D}{}^*_2(2460)^0\rho^+$	$<$ 4.7	$\times 10^{-3}$	CL=90%
Γ_{88}	$\overline{D}{}^0 D_s^+$	(1.09 $\pm$ 0.27)	%	
Γ_{89}	$D_{s0}(2317)^+\overline{D}{}^0 \times B(D_{s0}(2317)^+ \rightarrow D_s^+\pi^0)$	(7.4 $^{+2.3}_{-1.9}$)	$\times 10^{-4}$	
Γ_{90}	$D_{s0}(2317)^+\overline{D}{}^0 \times B(D_{s0}(2317)^+ \rightarrow D_s^{*+}\gamma)$	$<$ 7.6	$\times 10^{-4}$	CL=90%
Γ_{91}	$D_{s0}(2317)^+\overline{D}{}^*(2010)^0 \times B(D_{s0}(2317)^+ \rightarrow D_s^+\pi^0)$	(9 $\pm$ 7)	$\times 10^{-4}$	
Γ_{92}	$D_{sJ}(2457)^+\overline{D}{}^0 \times B(D_{sJ}(2457)^+ \rightarrow D_s^{*+}\pi^0)$	(1.4 $^{+0.6}_{-0.5}$)	$\times 10^{-3}$	S=1.3
Γ_{93}	$D_{sJ}(2457)^+\overline{D}{}^0 \times B(D_{sJ}(2457)^+ \rightarrow D_s^+\gamma)$	(4.7 $^{+1.4}_{-1.2}$)	$\times 10^{-4}$	
Γ_{94}	$D_{sJ}(2457)^+\overline{D}{}^0 \times B(D_{sJ}(2457)^+ \rightarrow D_s^+\pi^+\pi^-)$	$<$ 2.2	$\times 10^{-4}$	CL=90%
Γ_{95}	$D_{sJ}(2457)^+\overline{D}{}^0 \times B(D_{sJ}(2457)^+ \rightarrow D_s^+\pi^0)$	$<$ 2.7	$\times 10^{-4}$	CL=90%

Γ_{96}	$D_{sJ}(2457)^+\overline{D}{}^0 \times B(D_{sJ}(2457)^+ \rightarrow D_s^{*+}\gamma)$	$<$ 9.8	$\times 10^{-4}$	CL=90%
Γ_{97}	$D_{sJ}(2457)^+\overline{D}{}^*(2010)^0 \times B(D_{sJ}(2457)^+ \rightarrow D_s^{*+}\pi^0)$	(7.6 $^{+3.6}_{-2.9}$)	$\times 10^{-3}$	
Γ_{98}	$D_{sJ}(2457)^+\overline{D}{}^*(2010)^0 \times B(D_{sJ}(2457)^+ \rightarrow D_s^+\gamma)$	(1.4 $^{+0.7}_{-0.6}$)	$\times 10^{-3}$	
Γ_{99}	$\overline{D}{}^0 D_{sJ}(2536)^+ \times B(D_{sJ}(2536)^+ \rightarrow D^*(2007)^0K^+)$	$<$ 2	$\times 10^{-4}$	CL=90%
Γ_{100}	$\overline{D}{}^*(2007)^0 D_{sJ}(2536)^+ \times B(D_{sJ}(2536)^+ \rightarrow D^*(2007)^0K^+)$	$<$ 7	$\times 10^{-4}$	CL=90%
Γ_{101}	$\overline{D}{}^0 D_{sJ}(2573)^+ \times B(D_{sJ}(2573)^+ \rightarrow D^0K^+)$	$<$ 2	$\times 10^{-4}$	CL=90%
Γ_{102}	$\overline{D}{}^*(2007)^0 D_{sJ}(2573)^+ \times B(D_{sJ}(2573)^+ \rightarrow D^0K^+)$	$<$ 5	$\times 10^{-4}$	CL=90%
Γ_{103}	$\overline{D}{}^0 D_s^{*+}$	(7.2 $\pm$ 2.6)	$\times 10^{-3}$	
Γ_{104}	$\overline{D}{}^*(2007)^0 D_s^+$	(10 $\pm$ 4)	$\times 10^{-3}$	
Γ_{105}	$\overline{D}{}^*(2007)^0 D_s^{*+}$	(2.2 $\pm$ 0.7)	%	
Γ_{106}	$D_s^{(*)+}\overline{D}{}^{**0}$	(2.7 $\pm$ 1.2)	%	
Γ_{107}	$\overline{D}{}^*(2007)^0 D^*(2010)^+$	$<$ 1.1	%	CL=90%
Γ_{108}	$\overline{D}{}^0 D^*(2010)^+ + \overline{D}{}^*(2007)^0 D^+$	$<$ 1.3	%	CL=90%
Γ_{109}	$\overline{D}{}^0 D^*(2010)^+$	(4.6 $\pm$ 0.9)	$\times 10^{-4}$	
Γ_{110}	$\overline{D}{}^0 D^+$	(4.8 $\pm$ 1.0)	$\times 10^{-4}$	
Γ_{111}	$\overline{D}{}^0 D^+ K^0$	$<$ 2.8	$\times 10^{-3}$	CL=90%
Γ_{112}	$\overline{D}{}^*(2007)^0 D^+ K^0$	$<$ 6.1	$\times 10^{-3}$	CL=90%
Γ_{113}	$\overline{D}{}^0 \overline{D}{}^*(2010)^+ K^0$	(5.2 $\pm$ 1.2)	$\times 10^{-3}$	
Γ_{114}	$\overline{D}{}^*(2007)^0 D^*(2010)^+ K^0$	(7.8 $\pm$ 2.6)	$\times 10^{-3}$	
Γ_{115}	$\overline{D}{}^0 D^0 K^+$	(1.37 $\pm$ 0.32)	$\times 10^{-3}$	S=1.5
Γ_{116}	$\overline{D}{}^*(2010)^0 D^0 K^+$	$<$ 3.8	$\times 10^{-3}$	CL=90%
Γ_{117}	$\overline{D}{}^0 D^*(2007)^0 K^+$	(4.7 $\pm$ 1.0)	$\times 10^{-3}$	
Γ_{118}	$\overline{D}{}^*(2007)^0 D^*(2007)^0 K^+$	(5.3 $\pm$ 1.6)	$\times 10^{-3}$	
Γ_{119}	$D^- D^+ K^+$	$<$ 4	$\times 10^{-4}$	CL=90%
Γ_{120}	$D^- D^*(2010)^+ K^+$	$<$ 7	$\times 10^{-4}$	CL=90%
Γ_{121}	$D^*(2010)^- D^+ K^+$	(1.5 $\pm$ 0.4)	$\times 10^{-3}$	
Γ_{122}	$D^*(2010)^- D^*(2010)^+ K^+$	$<$ 1.8	$\times 10^{-3}$	CL=90%
Γ_{123}	$(\overline{D}+\overline{D}{}^*)(D+D^*)K$	(3.5 $\pm$ 0.6)	%	
Γ_{124}	$D_s^+\pi^0$	$<$ 1.7	$\times 10^{-4}$	CL=90%
Γ_{125}	$D_s^{*+}\pi^0$	$<$ 2.7	$\times 10^{-4}$	CL=90%
Γ_{126}	$D_s^+\eta$	$<$ 4	$\times 10^{-4}$	CL=90%
Γ_{127}	$D_s^{*+}\eta$	$<$ 6	$\times 10^{-4}$	CL=90%

Γ_{128}	$D_s^+ \rho^0$	$< 3.1 \times 10^{-4}$	CL=90%
Γ_{129}	$D_s^{*+} \rho^0$	$< 4 \times 10^{-4}$	CL=90%
Γ_{130}	$D_s^+ \omega$	$< 4 \times 10^{-4}$	CL=90%
Γ_{131}	$D_s^{*+} \omega$	$< 6 \times 10^{-4}$	CL=90%
Γ_{132}	$D_s^+ a_1(1260)^0$	$< 1.8 \times 10^{-3}$	CL=90%
Γ_{133}	$D_s^{*+} a_1(1260)^0$	$< 1.3 \times 10^{-3}$	CL=90%
Γ_{134}	$D_s^+ \phi$	$< 1.9 \times 10^{-6}$	CL=90%
Γ_{135}	$D_s^{*+} \phi$	$< 1.2 \times 10^{-5}$	CL=90%
Γ_{136}	$D_s^+ \overline{K}^0$	$< 9 \times 10^{-4}$	CL=90%
Γ_{137}	$D_s^{*+} \overline{K}^0$	$< 9 \times 10^{-4}$	CL=90%
Γ_{138}	$D_s^+ \overline{K}^*(892)^0$	$< 4 \times 10^{-4}$	CL=90%
Γ_{139}	$D_s^{*+} \overline{K}^*(892)^0$	$< 4 \times 10^{-4}$	CL=90%
Γ_{140}	$D_s^- \pi^+ K^+$	$< 7 \times 10^{-4}$	CL=90%
Γ_{141}	$D_s^{*-} \pi^+ K^+$	$< 9.8 \times 10^{-4}$	CL=90%
Γ_{142}	$D_s^- \pi^+ K^*(892)^+$	$< 5 \times 10^{-3}$	CL=90%
Γ_{143}	$D_s^{*-} \pi^+ K^*(892)^+$	$< 7 \times 10^{-3}$	CL=90%

Charmonium modes

Γ_{144}	$\eta_c K^+$	$(9.1 \pm 1.3) \times 10^{-4}$	
Γ_{145}	$\eta_c' K^+$	$(3.4 \pm 1.8) \times 10^{-4}$	
Γ_{146}	$J/\psi(1S) K^+$	$(1.008 \pm 0.035) \times 10^{-3}$	
Γ_{147}	$J/\psi(1S) K^+ \pi^+ \pi^-$	$(1.07 \pm 0.19) \times 10^{-3}$	S=1.9
Γ_{148}	$h_c(1P) K^+ \times$ B$(h_c(1P) \to J/\psi \pi^+ \pi^-)$	$< 3.4 \times 10^{-6}$	CL=90%
Γ_{149}	$X(3872) K^+$	$< 3.2 \times 10^{-4}$	CL=90%
Γ_{150}	$X(3872) K^+ \times$ B$(X \to J/\psi \pi^+ \pi^-)$	$(1.14 \pm 0.20) \times 10^{-5}$	
Γ_{151}	$X(3872) K^+ \times$ B$(X(3872) \to D^0 \overline{D}^0)$	$< 6.0 \times 10^{-5}$	CL=90%
Γ_{152}	$X(3872) K^+ \times$ B$(X(3872) \to D^+ D^-)$	$< 4.0 \times 10^{-5}$	CL=90%
Γ_{153}	$X(3872) K^+ \times$ B$(X(3872) \to D^0 \overline{D}^0 \pi^0)$	$< 6.0 \times 10^{-5}$	CL=90%
Γ_{154}	$X(3872) K^+ \times$ B$(X(3872) \to J/\psi(1S) \eta)$	$< 7.7 \times 10^{-6}$	CL=90%
Γ_{155}	$X(3872)^+ K^0 \times$ B$(X(3872)^+ \to J/\psi(1S) \pi^+ \pi^0)$ [e]	$< 2.2 \times 10^{-5}$	CL=90%
Γ_{156}	$Y(4260)^0 K^+ \times$ B$(Y^0 \to J/\psi \pi^+ \pi^-)$	$< 2.9 \times 10^{-5}$	CL=95%
Γ_{157}	$J/\psi(1S) K^*(892)^+$	$(1.41 \pm 0.08) \times 10^{-3}$	
Γ_{158}	$J/\psi(1S) K(1270)^+$	$(1.8 \pm 0.5) \times 10^{-3}$	
Γ_{159}	$J/\psi(1S) K(1400)^+$	$< 5 \times 10^{-4}$	CL=90%
Γ_{160}	$J/\psi(1S) \eta K^+$	$(1.08 \pm 0.33) \times 10^{-4}$	

Γ_{161}	$J/\psi(1S) \phi K^+$	$(5.2 \pm 1.7) \times 10^{-5}$	S=1.2
Γ_{162}	$J/\psi(1S) \pi^+$	$(4.9 \pm 0.6) \times 10^{-5}$	S=1.5
Γ_{163}	$J/\psi(1S) \rho^+$	$< 7.7 \times 10^{-4}$	CL=90%
Γ_{164}	$J/\psi(1S) a_1(1260)^+$	$< 1.2 \times 10^{-3}$	CL=90%
Γ_{165}	$J/\psi(1S) p \overline{\Lambda}$	$(1.18 \pm 0.31) \times 10^{-5}$	
Γ_{166}	$J/\psi(1S) \overline{\Sigma}^0 p$	$< 1.1 \times 10^{-5}$	CL=90%
Γ_{167}	$J/\psi(1S) D^+$	$< 1.2 \times 10^{-4}$	CL=90%
Γ_{168}	$J/\psi(1S) \overline{D}^0 \pi^+$	$< 2.5 \times 10^{-5}$	CL=90%
Γ_{169}	$\psi(2S) K^+$	$(6.48 \pm 0.35) \times 10^{-4}$	
Γ_{170}	$\psi(2S) K^*(892)^+$	$(6.7 \pm 1.4) \times 10^{-4}$	S=1.3
Γ_{171}	$\psi(2S) K^+ \pi^+ \pi^-$	$(1.9 \pm 1.2) \times 10^{-3}$	
Γ_{172}	$\psi(3770) K^+$	$(4.9 \pm 1.3) \times 10^{-4}$	
Γ_{173}	$\psi(3770) K^+ \times$ B$(\psi(3770) \to D^0 \overline{D}^0)$	$(3.4 \pm 0.9) \times 10^{-4}$	
Γ_{174}	$\psi(3770) K^+ \times$ B$(\psi(3770) \to D^+ D^- K^+)$	$(1.4 \pm 0.8) \times 10^{-4}$	
Γ_{175}	$\chi_{c0} \pi^+ \times$ B$(\chi_{c0} \to \pi^+ \pi^-)$	$< 3 \times 10^{-7}$	CL=90%
Γ_{176}	$\chi_{c0}(1P) K^+$	$(1.6 {}^{+0.5}_{-0.4}) \times 10^{-4}$	
Γ_{177}	$\chi_{c0} K^*(892)^+$	$< 2.86 \times 10^{-3}$	CL=90%
Γ_{178}	$\chi_{c2} K^+$	$< 2.9 \times 10^{-5}$	CL=90%
Γ_{179}	$\chi_{c2} K^*(892)^+$	$< 1.2 \times 10^{-5}$	CL=90%
Γ_{180}	$\chi_{c1}(1P) K^+$	$(5.3 \pm 0.7) \times 10^{-4}$	S=1.7
Γ_{181}	$\chi_{c1}(1P) K^*(892)^+$	$(3.6 \pm 0.9) \times 10^{-4}$	

K or K* modes

Γ_{182}	$K^0 \pi^+$	$(2.41 \pm 0.17) \times 10^{-5}$	S=1.4
Γ_{183}	$K^+ \pi^0$	$(1.21 \pm 0.08) \times 10^{-5}$	
Γ_{184}	$\eta' K^+$	$(7.05 \pm 0.35) \times 10^{-5}$	
Γ_{185}	$\eta' K^*(892)^+$	$< 1.4 \times 10^{-5}$	CL=90%
Γ_{186}	ηK^+	$(2.6 \pm 0.6) \times 10^{-6}$	S=1.3
Γ_{187}	$\eta K^*(892)^+$	$(2.6 \pm 0.4) \times 10^{-5}$	
Γ_{188}	ωK^+	$(5.1 \pm 0.7) \times 10^{-6}$	
Γ_{189}	$\omega K^*(892)^+$	$< 7.4 \times 10^{-6}$	CL=90%
Γ_{190}	$a_0^+ K^0$	$< 3.9 \times 10^{-6}$	CL=90%
Γ_{191}	$a_0^0 K^+$	$< 2.5 \times 10^{-6}$	CL=90%
Γ_{192}	$K^*(892)^0 \pi^+$	$(1.16 \pm 0.19) \times 10^{-5}$	S=1.8
Γ_{193}	$K^*(892)^+ \pi^0$	$(6.9 \pm 2.4) \times 10^{-6}$	
Γ_{194}	$K^+ \pi^- \pi^+$	$(5.6 \pm 0.9) \times 10^{-5}$	S=2.6
Γ_{195}	$K^+ \pi^- \pi^+$ nonresonant	$(3.1 {}^{+1.0}_{-0.8}) \times 10^{-6}$	
Γ_{196}	$K^+ f_0(980) \times$ B$(f_0 \to \pi^+ \pi^-)$	$(8.9 \pm 1.0) \times 10^{-6}$	
Γ_{197}	$f_2(1270)^0 K^+$	$< 2.3 \times 10^{-6}$	CL=90%
Γ_{198}	$f_0^*(1370)^0 K^+ \times$ B$(f_0^*(1370)^0 \to \pi^+ \pi^-)$	$< 1.07 \times 10^{-5}$	CL=90%

Γ_{199}	$\rho^0(1450) K^+ \times$ B($\rho^0(1450) \to \pi^+\pi^-$)	$< 1.17 \times 10^{-5}$	CL=90%
Γ_{200}	$f_0(1500) K^+ \times$ B($f_0(1500) \to \pi^+\pi^-$)	$< 4.4 \times 10^{-6}$	CL=90%
Γ_{201}	$f_2'(1525) K^+ \times$ B($f_2'(1525) \to \pi^+\pi^-$)	$< 3.4 \times 10^{-6}$	CL=90%
Γ_{202}	$K^+ \rho^0$	$(5.0 ^{+0.7}_{-0.8}) \times 10^{-6}$	
Γ_{203}	$K_0^*(1430)^0 \pi^+$	$(3.8 \pm 0.5) \times 10^{-5}$	
Γ_{204}	$K_2^*(1430)^0 \pi^+$	$< 6.9 \times 10^{-6}$	CL=90%
Γ_{205}	$K^*(1410)^0 \pi^+$	$< 4.5 \times 10^{-5}$	CL=90%
Γ_{206}	$K^*(1680)^0 \pi^+$	$< 1.2 \times 10^{-5}$	CL=90%
Γ_{207}	$K^- \pi^+ \pi^+$	$< 1.8 \times 10^{-6}$	CL=90%
Γ_{208}	$K^- \pi^+ \pi^+$ nonresonant	$< 5.6 \times 10^{-5}$	CL=90%
Γ_{209}	$K_1(1400)^0 \pi^+$	$< 2.6 \times 10^{-3}$	CL=90%
Γ_{210}	$K^0 \pi^+ \pi^0$	$< 6.6 \times 10^{-5}$	CL=90%
Γ_{211}	$K^0 \rho^+$	$< 4.8 \times 10^{-5}$	CL=90%
Γ_{212}	$K^*(892)^+ \pi^+ \pi^-$	$< 1.1 \times 10^{-3}$	CL=90%
Γ_{213}	$K^*(892)^+ \rho^0$	$(1.1 \pm 0.4) \times 10^{-5}$	
Γ_{214}	$K^*(892)^0 \rho^+$	$(8.9 \pm 2.1) \times 10^{-6}$	
Γ_{215}	$K^*(892)^+ K^*(892)^0$	$< 7.1 \times 10^{-5}$	CL=90%
Γ_{216}	$K_1(1400)^+ \rho^0$	$< 7.8 \times 10^{-4}$	CL=90%
Γ_{217}	$K_2^*(1430)^+ \rho^0$	$< 1.5 \times 10^{-3}$	CL=90%
Γ_{218}	$K^+ \overline{K}^0$	$(1.20 \pm 0.32) \times 10^{-6}$	
Γ_{219}	$\overline{K}^0 K^+ \pi^0$	$< 2.4 \times 10^{-5}$	CL=90%
Γ_{220}	$K^+ K_S^0 K_S^0$	$(1.15 \pm 0.13) \times 10^{-5}$	
Γ_{221}	$K_S^0 K_S^0 \pi^+$	$< 3.2 \times 10^{-6}$	CL=90%
Γ_{222}	$K^+ K^- \pi^+$	$< 6.3 \times 10^{-6}$	CL=90%
Γ_{223}	$K^+ K^- \pi^+$ nonresonant	$< 7.5 \times 10^{-5}$	CL=90%
Γ_{224}	$K^+ K^+ \pi^-$	$< 1.3 \times 10^{-6}$	CL=90%
Γ_{225}	$K^+ K^+ \pi^-$ nonresonant	$< 8.79 \times 10^{-5}$	CL=90%
Γ_{226}	$K^+ K^*(892)^0$	$< 5.3 \times 10^{-6}$	CL=90%
Γ_{227}	$K^+ f_J(2220)$		
Γ_{228}	$K^+ K^- K^+$	$(3.01 \pm 0.19) \times 10^{-5}$	
Γ_{229}	$K^+ \phi$	$(9.0 \pm 0.8) \times 10^{-6}$	S=1.3
Γ_{230}	$f_0(980) K^+ \times$ B($f_0(980) \to K^+ K^-$)	$< 2.9 \times 10^{-6}$	CL=90%
Γ_{231}	$a_2(1320) K^+ \times$ B($a_2(1320) \to K^+ K^-$)	$< 1.1 \times 10^{-6}$	CL=90%
Γ_{232}	$f_2'(1525) K^+ \times$ B($f_2'(1525) \to K^+ K^-$)	$< 4.9 \times 10^{-6}$	CL=90%
Γ_{233}	$\phi(1680) K^+ \times$ B($\phi(1680) \to K^+ K^-$)	$< 8 \times 10^{-7}$	CL=90%

Citation: W.-M. Yao *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006) (URL: http://pdg.lbl.gov)

Γ_{234}	$K^+ K^- K^+$ nonresonant	$(2.40 ^{+0.30}_{-0.62}) \times 10^{-5}$	
Γ_{235}	$K^*(892)^+ K^+ K^-$	$< 1.6 \times 10^{-3}$	CL=90%
Γ_{236}	$K^*(892)^+ \phi$	$(9.6 \pm 3.0) \times 10^{-6}$	S=1.9
Γ_{237}	$K_1(1400)^+ \phi$	$< 1.1 \times 10^{-3}$	CL=90%
Γ_{238}	$K_2^*(1430)^+ \phi$	$< 3.4 \times 10^{-3}$	CL=90%
Γ_{239}	$K^+ \phi \phi$	$(2.6 ^{+1.1}_{-0.9}) \times 10^{-6}$	
Γ_{240}	$K^*(892)^+ \gamma$	$(4.03 \pm 0.26) \times 10^{-5}$	
Γ_{241}	$K_1(1270)^+ \gamma$	$(4.3 \pm 1.3) \times 10^{-5}$	
Γ_{242}	$\eta K^+ \gamma$	$(8.4 \pm 1.8) \times 10^{-6}$	
Γ_{243}	$\phi K^+ \gamma$	$(3.4 \pm 1.0) \times 10^{-6}$	
Γ_{244}	$K^+ \pi^- \pi^+ \gamma$	$(2.50 \pm 0.28) \times 10^{-5}$	
Γ_{245}	$K^*(892)^0 \pi^+ \gamma$	$(2.0 ^{+0.7}_{-0.6}) \times 10^{-5}$	
Γ_{246}	$K^+ \rho^0 \gamma$	$< 2.0 \times 10^{-5}$	CL=90%
Γ_{247}	$K^+ \pi^- \pi^+ \gamma$ nonresonant	$< 9.2 \times 10^{-6}$	CL=90%
Γ_{248}	$K_1(1400)^+ \gamma$	$< 1.5 \times 10^{-5}$	
Γ_{249}	$K_2^*(1430)^+ \gamma$	$(1.4 \pm 0.4) \times 10^{-5}$	
Γ_{250}	$K^*(1680)^+ \gamma$	$< 1.9 \times 10^{-3}$	CL=90%
Γ_{251}	$K_3^*(1780)^+ \gamma$	$< 3.9 \times 10^{-5}$	CL=90%
Γ_{252}	$K_4^*(2045)^+ \gamma$	$< 9.9 \times 10^{-3}$	CL=90%

Light unflavored meson modes

Γ_{253}	$\rho^+ \gamma$	$< 1.8 \times 10^{-6}$	CL=90%
Γ_{254}	$\pi^+ \pi^0$	$(5.5 \pm 0.6) \times 10^{-6}$	
Γ_{255}	$\pi^+ \pi^+ \pi^-$	$(1.62 \pm 0.15) \times 10^{-5}$	
Γ_{256}	$\rho^0 \pi^+$	$(8.7 \pm 1.1) \times 10^{-6}$	
Γ_{257}	$\pi^+ f_0(980) \times$ B($f_0(980) \to \pi^+\pi^-$)	$< 3.0 \times 10^{-6}$	CL=90%
Γ_{258}	$\pi^+ f_2(1270)$	$(8.2 \pm 2.5) \times 10^{-6}$	
Γ_{259}	$\rho(1450)^0 \pi^+$	$< 2.3 \times 10^{-6}$	CL=90%
Γ_{260}	$f_0(1370) \pi^+ \times$B($f_0(1370) \to \pi^+\pi^-$)	$< 3.0 \times 10^{-6}$	CL=90%
Γ_{261}	$f_0(600) \pi^+ \times$B($f_0(600) \to \pi^+\pi^-$)	$< 4.1 \times 10^{-6}$	CL=90%
Γ_{262}	$\pi^+ \pi^- \pi^+$ nonresonant	$< 4.6 \times 10^{-6}$	CL=90%
Γ_{263}	$\pi^+ \pi^0 \pi^0$	$< 8.9 \times 10^{-4}$	CL=90%
Γ_{264}	$\rho^+ \pi^0$	$(1.20 \pm 0.19) \times 10^{-5}$	
Γ_{265}	$\pi^+ \pi^- \pi^+ \pi^0$	$< 4.0 \times 10^{-3}$	CL=90%
Γ_{266}	$\rho^+ \rho^0$	$(2.6 \pm 0.6) \times 10^{-5}$	
Γ_{267}	$a_1(1260)^+ \pi^0$	$< 1.7 \times 10^{-3}$	CL=90%
Γ_{268}	$a_1(1260)^0 \pi^+$	$< 9.0 \times 10^{-4}$	CL=90%
Γ_{269}	$\omega \pi^+$	$(5.9 \pm 1.0) \times 10^{-6}$	S=1.2
Γ_{270}	$\omega \rho^+$	$(1.3 \pm 0.4) \times 10^{-5}$	

	Mode		Fraction	Scale factor / Confidence level
Γ_{271}	$\eta\pi^+$		$(4.9 \pm 0.5) \times 10^{-6}$	
Γ_{272}	$\eta'\pi^+$		$(4.0 \pm 0.9) \times 10^{-6}$	
Γ_{273}	$\eta'\rho^+$		$< 2.2 \times 10^{-5}$	CL=90%
Γ_{274}	$\eta\rho^+$		$(8.4 \pm 2.2) \times 10^{-6}$	
Γ_{275}	$\phi\pi^+$		$< 4.1 \times 10^{-7}$	CL=90%
Γ_{276}	$\phi\rho^+$		$< 1.6 \times 10^{-5}$	
Γ_{277}	$a_0^0\pi^+$		$< 5.8 \times 10^{-6}$	CL=90%
Γ_{278}	$\pi^+\pi^+\pi^+\pi^-\pi^-$		$< 8.6 \times 10^{-4}$	CL=90%
Γ_{279}	$\rho^0 a_1(1260)^+$		$< 6.2 \times 10^{-4}$	CL=90%
Γ_{280}	$\rho^0 a_2(1320)^+$		$< 7.2 \times 10^{-4}$	CL=90%
Γ_{281}	$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0$		$< 6.3 \times 10^{-3}$	CL=90%
Γ_{282}	$a_1(1260)^+ a_1(1260)^0$		< 1.3 %	CL=90%

Charged particle ($h^\pm$) modes

$h^\pm = K^\pm$ or $\pi^\pm$

	Mode		Fraction	Scale factor / Confidence level
Γ_{283}	$h^+\pi^0$		$(1.6^{+0.7}_{-0.6}) \times 10^{-5}$	
Γ_{284}	ωh^+		$(1.38^{+0.27}_{-0.24}) \times 10^{-5}$	
Γ_{285}	$h^+ X^0$ (Familon)		$< 4.9 \times 10^{-5}$	CL=90%

Baryon modes

	Mode		Fraction	Scale factor / Confidence level
Γ_{286}	$p\overline{p}\pi^+$		$(3.1^{+0.8}_{-0.7}) \times 10^{-6}$	
Γ_{287}	$p\overline{p}\pi^+$ nonresonant		$< 5.3 \times 10^{-5}$	CL=90%
Γ_{288}	$p\overline{p}\pi^+\pi^+\pi^-$		$< 5.2 \times 10^{-4}$	CL=90%
Γ_{289}	$p\overline{p}K^+$		$(5.6 \pm 1.0) \times 10^{-6}$	S=2.4
Γ_{290}	$\Theta(1710)^{++}\overline{p} \times$ B$(\Theta(1710)^{++} \to pK^+)$	[f]	$< 9.1 \times 10^{-8}$	CL=90%
Γ_{291}	$f_J(2220)K^+ \times$ B$(f_J(2220) \to p\overline{p})$	[f]	$< 4.1 \times 10^{-7}$	CL=90%
Γ_{292}	$p\overline{\Lambda}(1520)$		$< 1.5 \times 10^{-6}$	CL=90%
Γ_{293}	$p\overline{p}K^+$ nonresonant		$< 8.9 \times 10^{-5}$	CL=90%
Γ_{294}	$p\overline{p}K^*(892)^+$		$(1.03^{+0.38}_{-0.33}) \times 10^{-5}$	
Γ_{295}	$p\overline{\Lambda}$		$< 4.9 \times 10^{-7}$	CL=90%
Γ_{296}	$p\overline{\Lambda}\gamma$		$(2.2 \pm 0.6) \times 10^{-6}$	
Γ_{297}	$p\overline{\Sigma}\gamma$		$< 4.6 \times 10^{-6}$	CL=90%
Γ_{298}	$p\overline{\Lambda}\pi^+\pi^-$		$< 2.0 \times 10^{-4}$	CL=90%
Γ_{299}	$\Lambda\overline{\Lambda}\pi^+$		$< 2.8 \times 10^{-6}$	CL=90%
Γ_{300}	$\Lambda\overline{\Lambda}K^+$		$(2.9^{+1.0}_{-0.8}) \times 10^{-6}$	
Γ_{301}	$\overline{\Delta}^0 p$		$< 3.8 \times 10^{-4}$	CL=90%
Γ_{302}	$\Delta^{++}\overline{p}$		$< 1.5 \times 10^{-4}$	CL=90%
Γ_{303}	$D^+ p\overline{p}$		$< 1.5 \times 10^{-5}$	CL=90%
Γ_{304}	$D^*(2010)^+ p\overline{p}$		$< 1.5 \times 10^{-5}$	CL=90%

	Mode		Fraction	Scale factor / Confidence level
Γ_{305}	$\overline{\Lambda}_c^- p\pi^+$		$(2.1 \pm 0.7) \times 10^{-4}$	
Γ_{306}	$\overline{\Lambda}_c^- p\pi^+\pi^0$		$(1.8 \pm 0.6) \times 10^{-3}$	
Γ_{307}	$\overline{\Lambda}_c^- p\pi^+\pi^+\pi^-$		$(2.3 \pm 0.7) \times 10^{-3}$	
Γ_{308}	$\overline{\Lambda}_c^- p\pi^+\pi^+\pi^-\pi^0$		< 1.34 %	CL=90%
Γ_{309}	$\overline{\Sigma}_c(2455)^0 p$		$< 8 \times 10^{-5}$	CL=90%
Γ_{310}	$\overline{\Sigma}_c(2520)^0 p$		$< 4.6 \times 10^{-5}$	CL=90%
Γ_{311}	$\overline{\Sigma}_c(2455)^0 p\pi^0$		$(4.4 \pm 1.8) \times 10^{-4}$	
Γ_{312}	$\overline{\Sigma}_c(2455)^0 p\pi^-\pi^+$		$(4.4 \pm 1.7) \times 10^{-4}$	
Γ_{313}	$\overline{\Sigma}_c(2455)^{--} p\pi^+\pi^+$		$(2.8 \pm 1.2) \times 10^{-4}$	
Γ_{314}	$\overline{\Lambda}_c(2593)^- / \overline{\Lambda}_c(2625)^- p\pi^+$		$< 1.9 \times 10^{-4}$	CL=90%

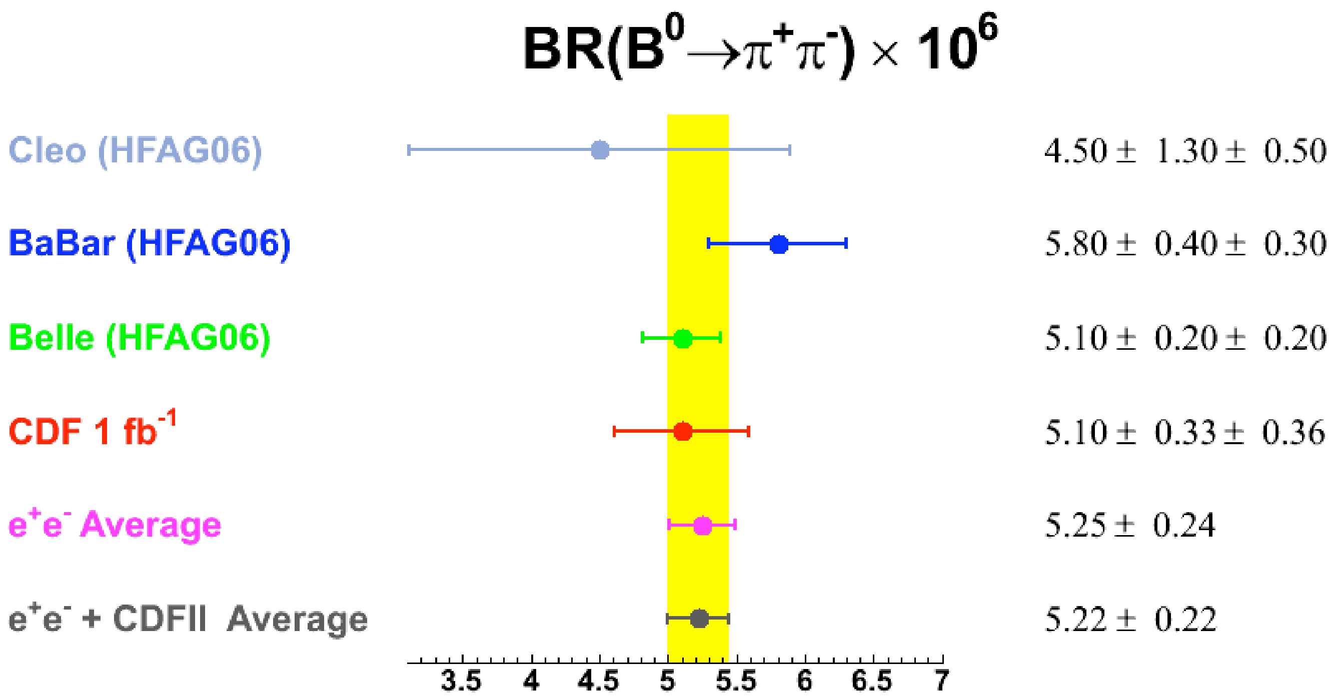
Lepton Family number (*LF*) or Lepton number (*L*) violating modes, or $\Delta B = 1$ weak neutral current (*B1*) modes

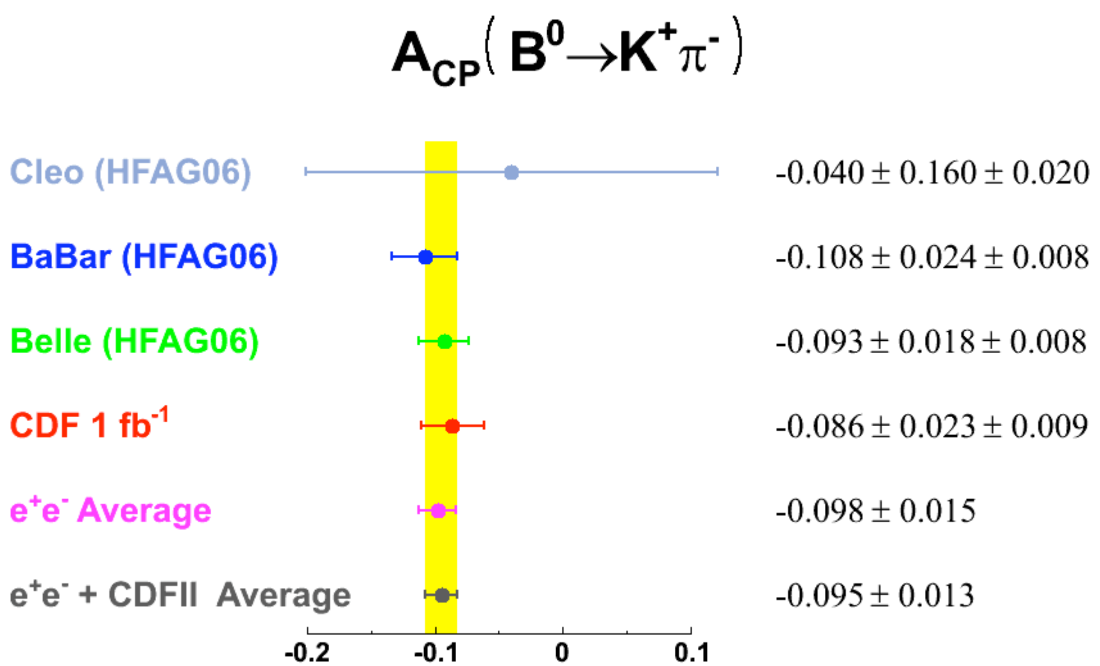
	Mode			Fraction	Scale factor / Confidence level
Γ_{315}	$\pi^+ e^+ e^-$	*B1*		$< 3.9 \times 10^{-3}$	CL=90%
Γ_{316}	$\pi^+\mu^+\mu^-$	*B1*		$< 9.1 \times 10^{-3}$	CL=90%
Γ_{317}	$\pi^+\nu\overline{\nu}$	*B1*		$< 1.0 \times 10^{-4}$	CL=90%
Γ_{318}	$K^+ e^+ e^-$	*B1*		$(8.0^{+2.2}_{-1.9}) \times 10^{-7}$	S=1.4
Γ_{319}	$K^+\mu^+\mu^-$	*B1*		$(3.4^{+1.9}_{-1.4}) \times 10^{-7}$	S=1.7
Γ_{320}	$K^+\ell^+\ell^-$	*B1*	[a]	$(5.3 \pm 1.1) \times 10^{-7}$	
Γ_{321}	$K^+\overline{\nu}\nu$	*B1*		$< 5.2 \times 10^{-5}$	CL=90%
Γ_{322}	$K^*(892)^+ e^+ e^-$	*B1*		$< 4.6 \times 10^{-6}$	CL=90%
Γ_{323}	$K^*(892)^+\mu^+\mu^-$	*B1*		$< 2.2 \times 10^{-6}$	CL=90%
Γ_{324}	$K^*(892)^+\ell^+\ell^-$	*B1*	[a]	$< 2.2 \times 10^{-6}$	CL=90%
Γ_{325}	$\pi^+ e^+\mu^-$	*LF*		$< 6.4 \times 10^{-3}$	CL=90%
Γ_{326}	$\pi^+ e^-\mu^+$	*LF*		$< 6.4 \times 10^{-3}$	CL=90%
Γ_{327}	$K^+ e^+\mu^-$	*LF*		$< 8 \times 10^{-7}$	CL=90%
Γ_{328}	$K^+ e^-\mu^+$	*LF*		$< 6.4 \times 10^{-3}$	CL=90%
Γ_{329}	$K^*(892)^+ e^\pm\mu^\mp$	*LF*		$< 7.9 \times 10^{-6}$	CL=90%
Γ_{330}	$\pi^- e^+ e^+$	*L*		$< 1.6 \times 10^{-6}$	CL=90%
Γ_{331}	$\pi^-\mu^+\mu^+$	*L*		$< 1.4 \times 10^{-6}$	CL=90%
Γ_{332}	$\pi^- e^+\mu^+$	*L*		$< 1.3 \times 10^{-6}$	CL=90%
Γ_{333}	$\rho^- e^+ e^+$	*L*		$< 2.6 \times 10^{-6}$	CL=90%
Γ_{334}	$\rho^-\mu^+\mu^+$	*L*		$< 5.0 \times 10^{-6}$	CL=90%
Γ_{335}	$\rho^- e^+\mu^+$	*L*		$< 3.3 \times 10^{-6}$	CL=90%
Γ_{336}	$K^- e^+ e^+$	*L*		$< 1.0 \times 10^{-6}$	CL=90%
Γ_{337}	$K^-\mu^+\mu^+$	*L*		$< 1.8 \times 10^{-6}$	CL=90%
Γ_{338}	$K^- e^+\mu^+$	*L*		$< 2.0 \times 10^{-6}$	CL=90%
Γ_{339}	$K^*(892)^- e^+ e^+$	*L*		$< 2.8 \times 10^{-6}$	CL=90%
Γ_{340}	$K^*(892)^-\mu^+\mu^+$	*L*		$< 8.3 \times 10^{-6}$	CL=90%
Γ_{341}	$K^*(892)^- e^+\mu^+$	*L*		$< 4.4 \times 10^{-6}$	CL=90%

Hadronic B-decays at hadron machines

see M. Herndon's lecture,
also G. Punzi's wine & cheese, Oct '06

- Lots of B_s -decays and Λ_b -decays remain to be discovered
  - B_s decay listing is 16 pages in PDG, Λ_b listing is 7 pages long.
  - B^0 listing is 146 pages!
- Hadron machines are much noisier enviroment than e^+e^-, but produce more b-hadrons
  - Fewer channels can be reconstructed, but competitive in those.





Challenging for theory!

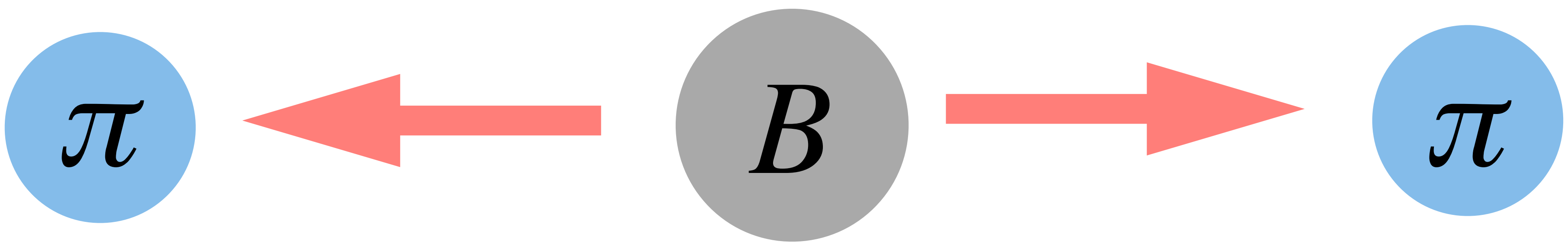
- Exclusive final states
  - Hadronization effects are important, even in the heavy quark limit. Cannot use OPE.
- >1 hadron in final state
  - Difficult for lattice
- Energetic light hadrons $E_{\mathrm{M}} \approx m_B/2$
  - HQET not applicable (expansion in E_M/m_B)
  - Difficult for lattice $E_{\mathrm{M}} \geq 1/a$

Theoretical methods

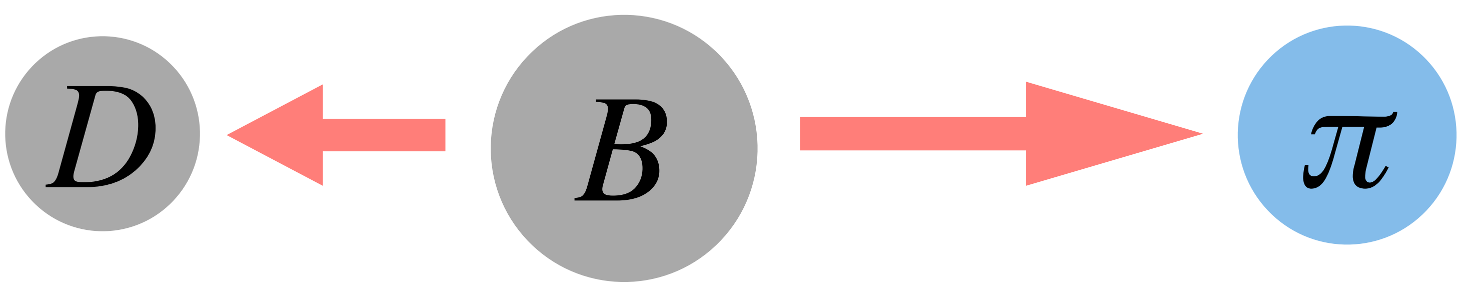
- Weak effective Hamiltonian
  - 10 different operators for $B \to M_1\, M_2$. (Tree, QCD penguins and EW penguin operators.)
- Symmetries of QCD
  - C, P, T
  - Approximate flavor symmetries:
    - Isospin: $\frac{m_{u,d}}{\Lambda} \sim 0.03 \ll 1$
    - SU(3): $\frac{m_{u,d}}{\Lambda} \ll 1,\ \frac{m_s}{\Lambda} \sim 0.3 \ll 1$
- Factorization theorems in the limit $m_b \to \infty$. Soft-collinear effective theory (SCET).
  - Expansion in $\frac{\Lambda}{E_M} \sim \frac{2\Lambda}{m_b} \sim 0.2 \ll 1$

Kinematics

- Decay produces energetic light mesons



$$E_\pi = \frac{M_B}{2} \gg M_\pi$$



$$E_\pi = \frac{M_B^2 - M_D^2 - M_\pi^2}{2M_B} = 2.3\,\mathrm{GeV}$$

- Expand in $\Lambda_{\mathrm{QCD}}/m_{\mathrm{b}} \sim \Lambda_{\mathrm{QCD}}/E_\pi$

Focus of lecture

- *D*-modes: $\mathrm{Br}(B \to D\, M) \sim 10^{-4} - 10^{-3}$
  - Not very sensitive to new physics
    - Tree-level in weak interaction
    - Good testing ground for theoretical methods
- Charmless decays: $\mathrm{Br}(B \to M_1\, M_2) \sim 10^{-6} - 10^{-4}$
  - Sensitive to new physics
    - CKM suppression
    - Penguin and tree contributions
- Omit charmonium or baryonic modes and higher multiplicity in final states.
  - Above two categories are complicated enough...

$B \to DM$

Factorization & Soft-Collinear Effective Theory

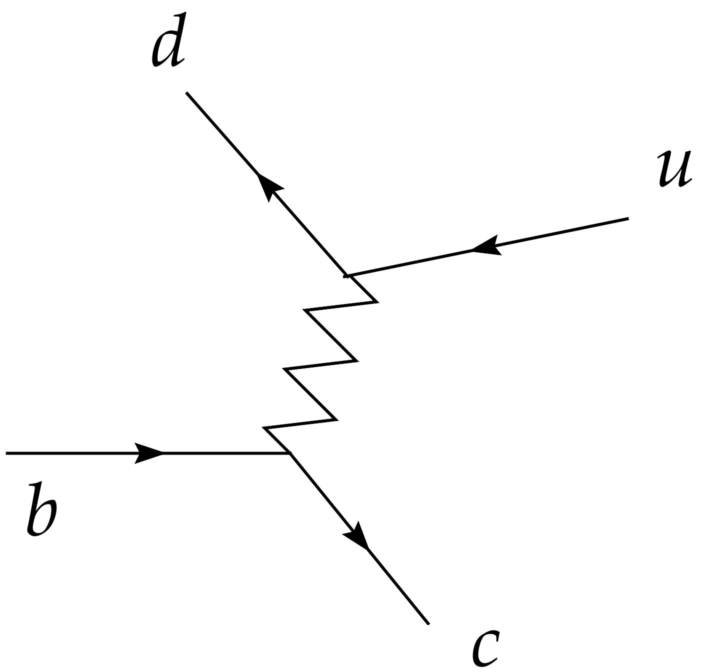
$B \to D\pi$

- Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{ud}^* V_{cb} \left(C_0 O_0 + C_8 O_8 \right)$$

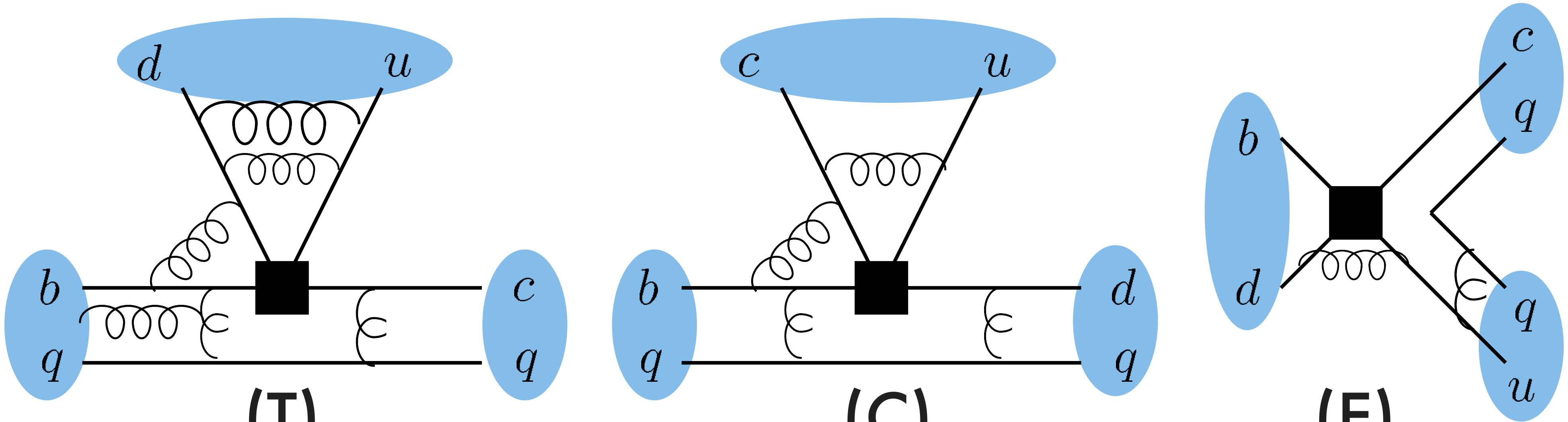
$$O_0 = \bar{c}\gamma^\mu (1-\gamma_5) b \, \bar{d}\gamma_\mu (1-\gamma_5) u \, ,$$

$$O_8 = \bar{c}\gamma^\mu (1-\gamma_5) T^A b \, \bar{d}\gamma_\mu (1-\gamma_5) T^A u$$



- No penguins.
- $C_0 \equiv C_0(\mu)$, $C_8 \equiv C_8(\mu)$.
- $C_0(M_W)=1+O(\alpha_s)$, $C_8\,(M_W)=O(\alpha_s)$.

Flavor topologies



(T) tree | (C) color suppressed tree | (E) weak annihilation

- Additional gluons not suppressed, cannot evaluate decay in perturbation theory!
- Topologies
  - $B_d \to D^+ \pi^-$: (T) + (E)
  - $B_d \to D^0 \pi^0$: (C) - (E)
  - $B^- \to D^0 \pi^-$: (T) + (C)
- Will find that (T) is factorizable and (C), (E) are non-factorizable and Λ_{QCD}/m_b suppressed.

Isospin analysis

- D π can be isospin 1/2 or 3/2.

$$A_{+-} = A(\bar{B}^0 \to D^+\pi^-) \; = \; \frac{1}{\sqrt{3}}A_{3/2} + \sqrt{\frac{2}{3}}A_{1/2} = T + E\,,$$

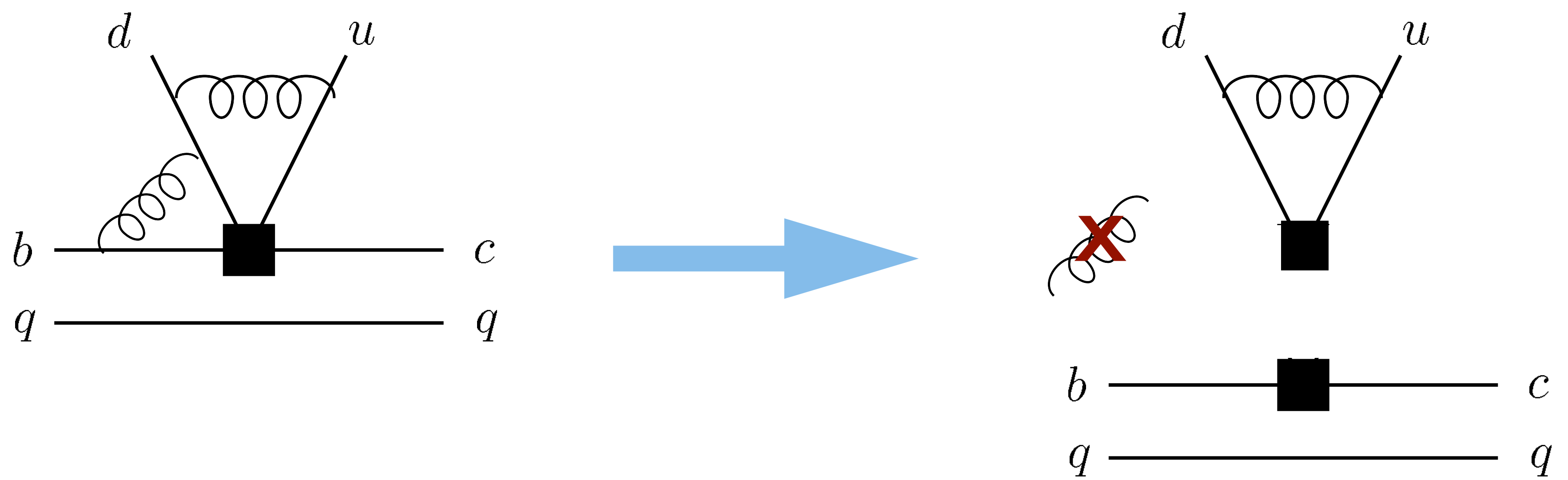
$$A_{\,0-} = A(B^- \to D^0\,\pi^-) \; = \; \sqrt{3}A_{3/2} = T + C\,,$$

$$A_{\,00} = A(\bar{B}^0 \to D^0\,\pi^0\,) \; = \; \sqrt{\frac{2}{3}}A_{3/2} - \frac{1}{\sqrt{3}}A_{1/2} = \frac{1}{\sqrt{2}}(C - E)$$

- Three observables:

$$|A_{3/2}|\,, \quad |A_{1/2}|\,, \quad \delta = \arg(A_{1/2}A^*_{3/2})$$

Naive factorization for $B_d \to D^+ \pi^-$



- Replace

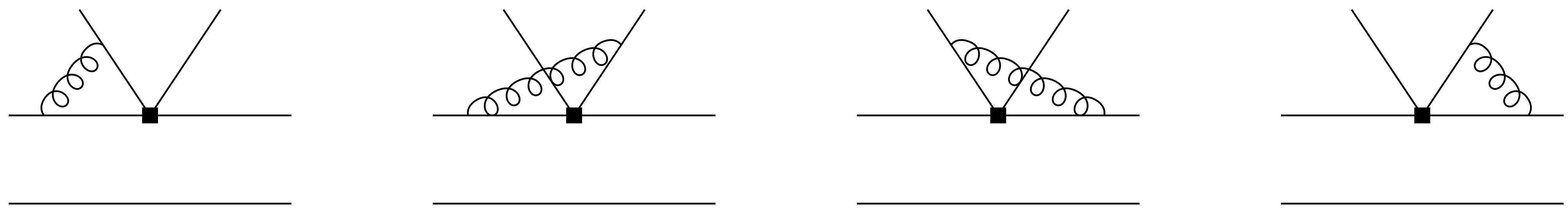
$$\langle D^+\pi^-|\,(\bar{c}b)_{V-A}\,(\bar{d}u)_{V-A}\,|B\rangle$$

$$\longrightarrow \langle\pi^-|\,(\bar{d}u)_{V-A}\,|0\rangle\;\langle D^+|\,(\bar{c}b)_{V-A}|B\rangle$$

$$f_\pi \qquad\qquad F_{B\to D}(M_\pi^2)$$

- This is a model! Not even consistent (result for decay rate becomes scale dependent), but works numerically well.

(QCD) factorization for $B_d \to D^+ \pi^-$



- Cannot leave out interactions with outgoing π.
- In the limit $m_b \to \infty$, m_c/m_b fixed
  - pion becomes energetic
    - $E_\pi = (m_B^2 - m_D^2)/2m_B \to \infty$
  - the interactions are suppressed by $\alpha_s(m_b)$
    - evaluate in perturbation theory
    - lowest order: naive factorization
- Bjorken: "color transparency"

Factorization theorem

$$\langle D^+\pi^-|\,O_{0,8}\,|\bar{B}\rangle = \frac{iM_B E_\pi f_\pi}{2} F_{B\to D}(0)\int_0^1 T_{0,8}(x,\mu)\phi_\pi(x,\mu) + \mathcal{O}(\frac{\Lambda_{QCD}}{m_b})$$

Proposed by Politzer and Wise '91, checked to 2 loops by Beneke et al. '00, all order analysis using SCET Bauer et al. '01

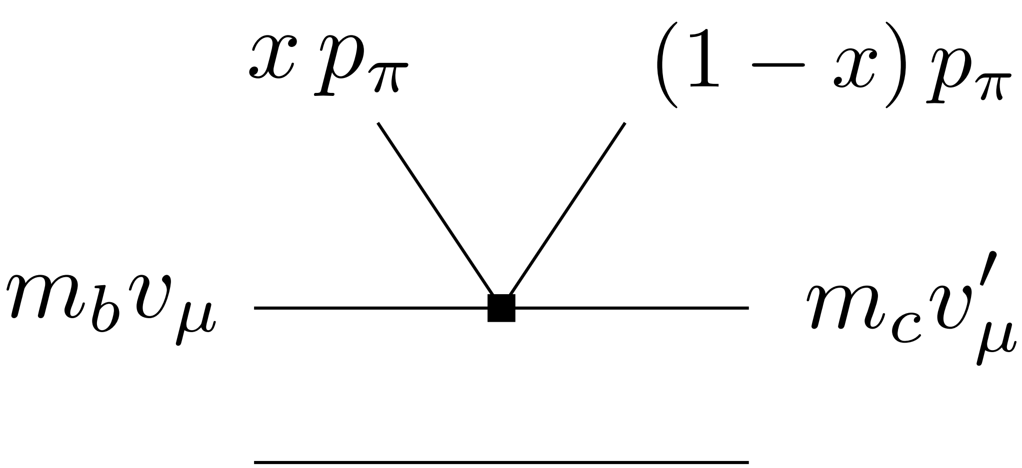
- T_0(x,μ) and T_8(x,μ) are hard scattering kernels
    - calculable in perturbation theory

$$T_0(x,\mu) = 1 + \mathcal{O}(\alpha_s^2) \quad T_8(x,\mu) = \frac{\alpha_s}{4\pi}\frac{N_c^2-1}{4N_c^2}\left[-6\ln\frac{\mu^2}{m_b^2} + f(x, m_c/m_b)\right] + \mathcal{O}(\alpha_s^2)$$

- ϕ_π (x,μ) is the "leading twist light-cone distribution amplitude" of the pion.
    - non-perturbative

Hard scattering kernel $T(x,\mu)$

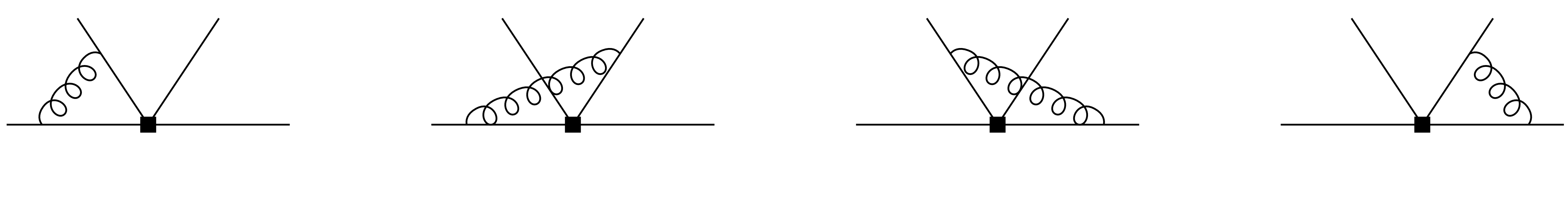
- Lowest order in α_s:



$$
\begin{aligned}
p_b &= m_b v + \mathcal{O}(\Lambda_{\mathrm{QCD}}) \\
p_c &= m_c v' + \mathcal{O}(\Lambda_{\mathrm{QCD}}) \\
p_d &= x\,p_\pi + \mathcal{O}(\Lambda_{\mathrm{QCD}}) \\
p_u &= (1-x)p_\pi + \mathcal{O}(\Lambda_{\mathrm{QCD}})
\end{aligned}
$$

  - Have expanded momenta. Can neglect pion mass and perpendicular momentum of quarks.

- First order in α_s:



Light-cone distribution amplitude

arbitrary Dirac matrix

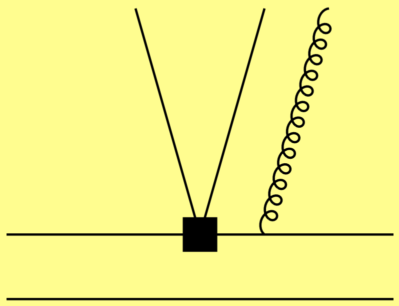
$$\langle \pi^-(p_\pi)|\bar{d}(y)\Gamma u(0)|0\rangle \Big|_{y^2=0} = \frac{if_\pi}{4}\mathrm{Tr}\left[\Gamma \not{p}_\pi \gamma_5\right] \int_0^1 dx\, e^{ixy\cdot p_\pi} \phi_\pi(x,\mu)$$

- Amplitude for an up anti-quark with momentum fraction x and a down quark with fraction (1-x) to hadronize into a pion.
- Normalized to 1: $\int_0^1 dx\, \phi_\pi(x,\mu) = 1$
- Asymptotic DA: $\phi_\pi(x,\mu) = 6x(1-x)$ for $\mu \to \infty$
  - Often used for simplicity, but might not be adequate at $\mu \sim m_b$.

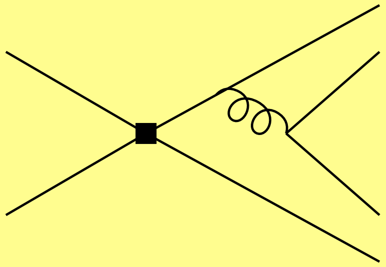
Questions:

Beneke et al. '00. (112pp!)

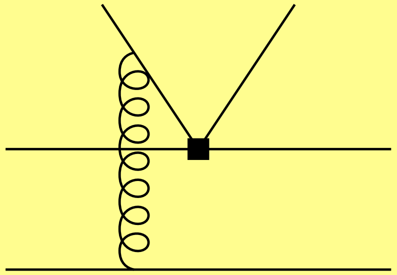
Some Λ/m_b power suppressed effects:



higher fock state



annihilation



spectator interaction

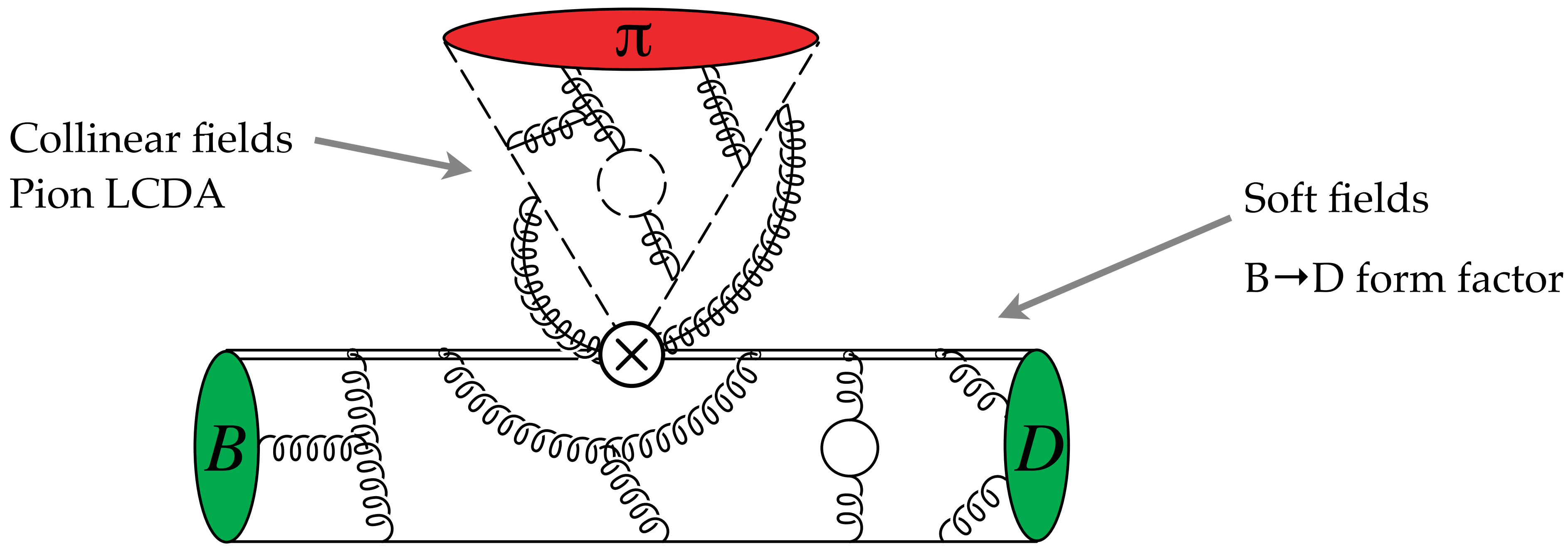
- Is the hard scattering kernel insensitive to low energy QCD effects?
  - Individual diagrams need IR cut-off (e.g. gluon mass), but sum is well defined to 2-loop accuracy.
- Is the integral over x convergent?
  - OK at 1-loop order.
- Contribution from higher fock states?
  - Tree-level contributions suppressed as Λ/m_b
- Contribution from other two flavor topologies, such as weak annihilation?
  - Tree-level contributions suppressed as Λ/m_b

Soft-collinear effective theory

Bauer, Pirjol, Stewart, ...

- Provides a systematic framework to perform expansion in $\Lambda_{QCD}/E_\pi \sim \Lambda_{QCD}/m_b$ for processes with light energetic hadrons in final state.
  - All order (in α_s) answers to the questions on the previous page.
- Splits QCD quark and gluon fields into
  - "Soft fields": HQET Lagrangian for the partons inside the B- and D-meson.
  - "Collinear fields": partons inside energetic light mesons.
  - "Messenger fields": low-energy interaction between light mesons and B- and D-mesons.

Factorization in SCET



- At leading power messenger fields decouple → factorization
- Hard scattering kernel T becomes Wilson coefficient of SCET operator.
- Matrix element of soft fields: B →D form factor.
- Matrix element of collinear fields: π light-cone dist. amp.

Confrontation with data

Decay	Br(10^{-3})	$\lvert A\rvert$ (10^{-7} GeV)	Decay	Br(10^{-3})	$\lvert A\rvert$ (10^{-7} GeV)
$\bar{B}^0 \to D^+\pi^-$	2.76 ± 0.25	5.99 ± 0.27	$\bar{B}^0 \to D^{*+}\pi^-$	2.76 ± 0.21	6.06 ± 0.23
$B^- \to D^0\pi^-$	4.98 ± 0.29	7.72 ± 0.22	$B^- \to D^{*0}\pi^-$	4.6 ± 0.4	7.50 ± 0.33
$\bar{B}^0 \to D^0\pi^0$	0.25 ± 0.02	1.81 ± 0.08	$\bar{B}^0 \to D^{*0}\pi^0$	0.28 ± 0.05	1.95 ± 0.18
$\bar{B}^0 \to D^+\rho^-$	7.7 ± 1.3	10.2 ± 0.9	$\bar{B}^0 \to D^{*+}\rho^-$	6.8 ± 0.9	9.10 ± 0.61
$B^- \to D^0\rho^-$	13.4 ± 1.8	12.9 ± 0.9	$B^- \to D^{*0}\rho^-$	9.8 ± 1.7	10.5 ± 0.92
$\bar{B}^0 \to D^0\rho^0$	0.29 ± 0.11	1.97 ± 0.37	$\bar{B}^0 \to D^{*0}\rho^0$	0.37±0.10	2.2±1.0

from a talk by I. Stewart, May '05. See http://hfag.phys.ntu.edu.tw/b2charm/ for up to date results.

- Size of Br($B_d \to D^+ M^-$) agrees with factorization prediction. ✓
- Power suppressed Br($B_d \to D^0 M^0$) indeed small. (Additional color suppression.) ✓
- Br($B \to D\,\pi$) ≈ Br($B_d \to D^*\,\pi$) holds. Even for power suppressed $B_d \to D^0 M^0$ (Mantry, Pirjol and Stewart '03). ✓

$$\frac{|A(B^- \to D^0\rho^-)|}{|A(B^- \to D^0\pi^-)|} = 1.67 \pm 0.12 \simeq \frac{f_\rho}{f_\pi} ✓, \qquad \frac{|V_{ud}||A(B^- \to D^0K^-)|}{|V_{us}||A(B^- \to D^0\pi^-)|} = 1.20 \pm 0.10 \simeq \frac{f_K}{f_\pi} ✓$$

Confrontation with Data

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from a talk by I. Stewart, May '05. See http://hfag.phys.ntu.edu.tw/b2charm/ for up to date numerical results.

- Significant difference between Br($B_d \to D^+ M^-$) and Br($B^- \to D^0 M^-$) which are equal in heavy quark limit.

$$\frac{|A_{0-}|}{|A_{+-}|} = \begin{cases} 0.77 \pm 0.05 & \text{for } D\pi \\ 0.81 \pm 0.05 & \text{for } D^*\pi \end{cases}$$

  - 20-30% in amplitude $\to$ 40-60% in BR!
- Sizable phase $\delta = \arg(A_{1/2}A^*_{3/2}) \sim 30^\circ$
  - Suppressed by $\Lambda_{\mathrm{QCD}}/m_b$

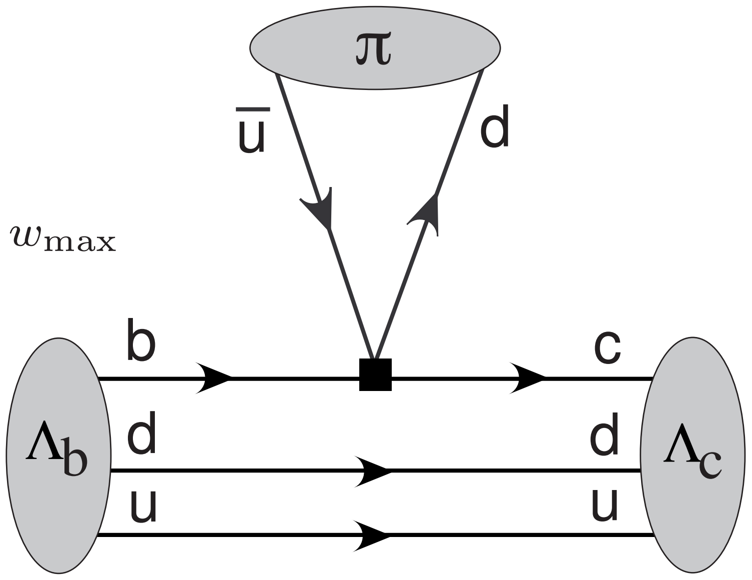
b-baryons

Leibovich, Ligeti, Stewart & Wise ‘03

- CDF ‘05 has measured $\mathcal{B}(\Lambda_b \to \Lambda_c^+ \pi^-)$
- Same factorization theorem holds for b-baryons. Identical hard-scattering kernel, but need $F_{\Lambda_b \to \Lambda_c}(M_\pi^2 \approx 0)$

$$\Gamma(\Lambda_b \to \Lambda_c \pi) = \frac{3\pi^2 (C_1 + C_2/3)^2 \, |V_{ud}|^2 f_\pi^2}{m_{\Lambda_b}^2 \, r_\Lambda} \left(\frac{\mathrm{d}\Gamma(\Lambda_b \to \Lambda_c \ell \bar{\nu})}{\mathrm{d}w} \right)_{w_{\max}}$$

$$r_\Lambda = m_{\Lambda_c}/m_{\Lambda_b}, \; w = v \cdot v' = (m_{\Lambda_b}^2 + m_{\Lambda_c}^2 - q^2)/(2 m_{\Lambda_b} m_{\Lambda_c}),$$

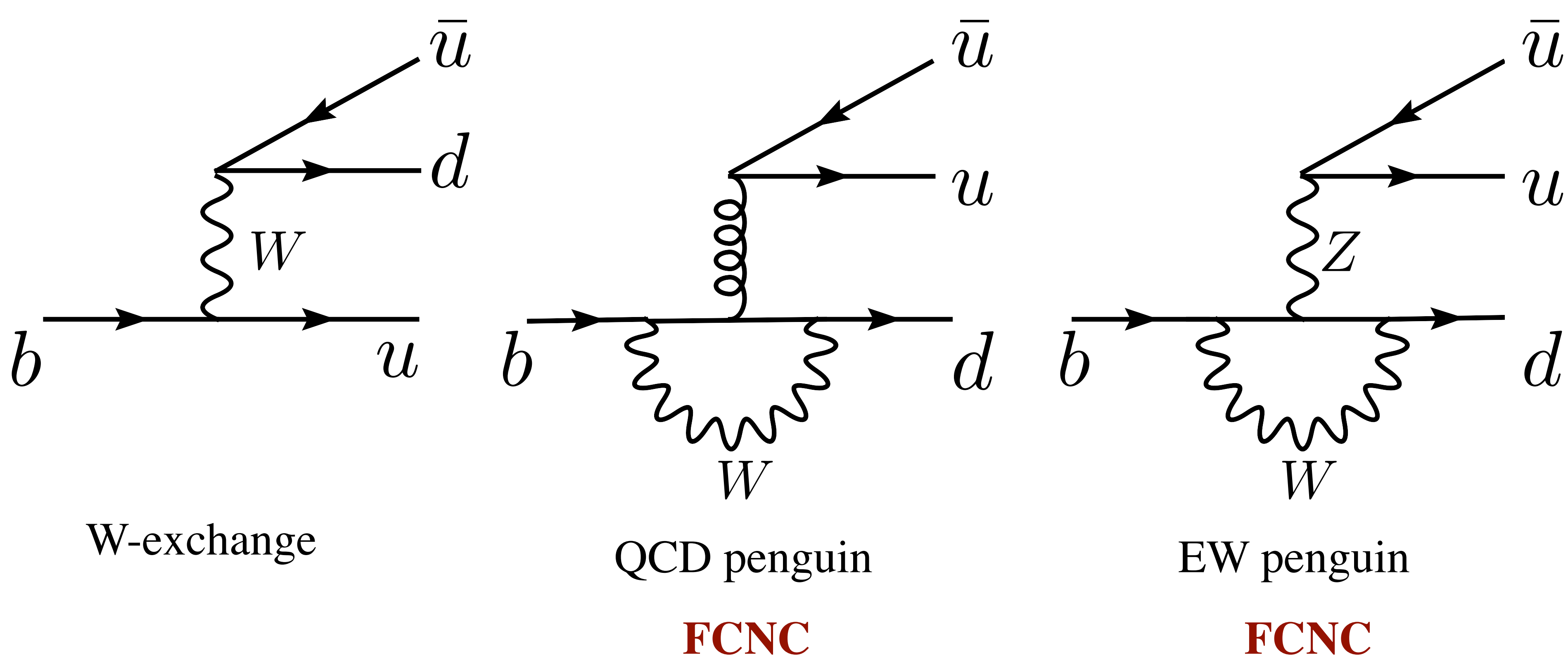


$$\frac{Br(\Lambda_b \to \Sigma_c^* \pi)}{Br(\Lambda_b \to \Sigma_c \pi)} = 2\,, \quad \frac{Br(\Lambda_b \to \Sigma_c^* \rho)}{Br(\Lambda_b \to \Sigma_c \rho)} = 2 \qquad \frac{Br(\Lambda_b \to \Xi_c^* K)}{Br(\Lambda_b \to \Xi_c' K)} = 2\,, \quad \frac{Br(\Lambda_b \to \Xi_c^* K_\parallel^*)}{Br(\Lambda_b \to \Xi_c' K_\parallel^*)} = 2$$

$$\mathbf{B} \longrightarrow M_1\ M_2$$

$B \to M_1 M_2$

- Rare: BR ~ 10^{-6} - 10^{-4}, about 100 times smaller than in $B_d \to D^+ M^-$. $|V_{ub}/V_{cb}| \sim 0.1$.
- Sensitive to new physics: penguin as well as tree-level contributions.
  - e.g. for $B \to \pi\pi$



Weak Hamiltonian

$$\lambda_p = V_{pb} V_{ps}^*$$

$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \Big(C_1\, Q_1^p + C_2\, Q_2^p + \sum_{i=3,\ldots,10} C_i\, Q_i + C_{7\gamma}\, Q_{7\gamma} + C_{8g}\, Q_{8g} \Big) + \text{h.c.}$$

Tree operators

$$Q_1^p = (\bar{p}b)_{V-A}(\bar{s}p)_{V-A}\,, \qquad Q_2^p = (\bar{p}_i b_j)_{V-A}(\bar{s}_j p_i)_{V-A}\,,$$

Penguin operators

$$Q_3 = (\bar{s}b)_{V-A} \textstyle\sum_q (\bar{q}q)_{V-A}\,, \qquad Q_4 = (\bar{s}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V-A}\,,$$

$$Q_5 = (\bar{s}b)_{V-A} \textstyle\sum_q (\bar{q}q)_{V+A}\,, \qquad Q_6 = (\bar{s}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V+A}\,,$$

EW penguin operators

$$Q_7 = (\bar{s}b)_{V-A} \textstyle\sum_q \frac{3}{2} e_q (\bar{q}q)_{V+A}\,, \qquad Q_8 = (\bar{s}_i b_j)_{V-A} \sum_q \frac{3}{2} e_q (\bar{q}_j q_i)_{V+A}\,,$$

$$Q_9 = (\bar{s}b)_{V-A} \textstyle\sum_q \frac{3}{2} e_q (\bar{q}q)_{V-A}\,, \qquad Q_{10} = (\bar{s}_i b_j)_{V-A} \sum_q \frac{3}{2} e_q (\bar{q}_j q_i)_{V-A}\,,$$

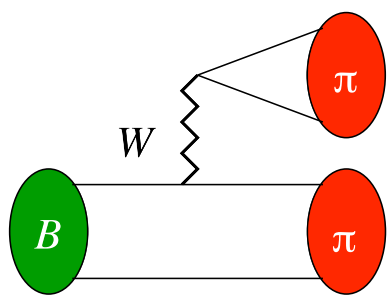
- Hierarchy of Wilson coefficients

$$C_1 \gtrsim C_2 \gg C_{3-6} \gg C_{9,10} \gtrsim C_{7,8}$$

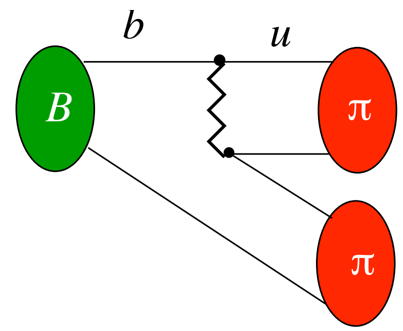
often neglected

$$C_{1-10}(m_b) = \{1.107\,, -.249\,, .011\,, -.026\,, .008\,, -.031\,, 4.9\times10^{-4}\,, 4.6\times10^{-4}\,, -9.8\times10^{-3}\,, 1.9\times10^{-3}\}\,.$$

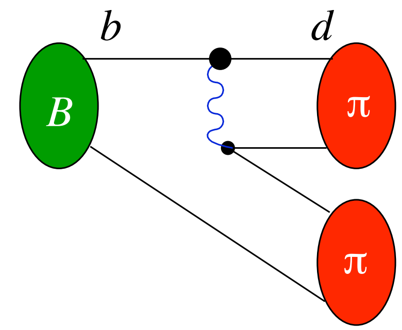
Flavor topologies



Tree (T)

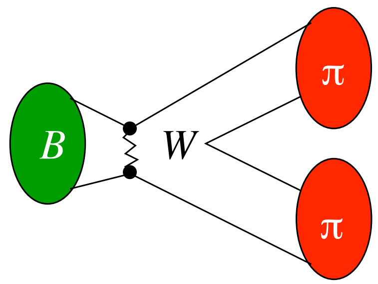


Color-suppressed (C)

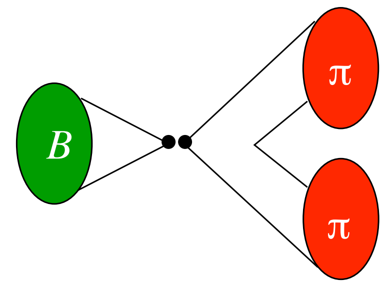


Penguin (P)

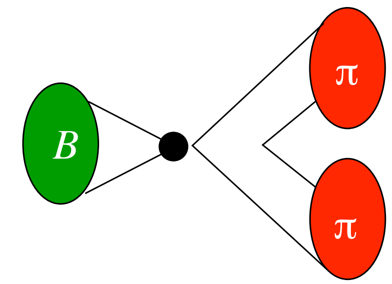
+ EWPs



W-exchange (E)



Weak annihilation (A)

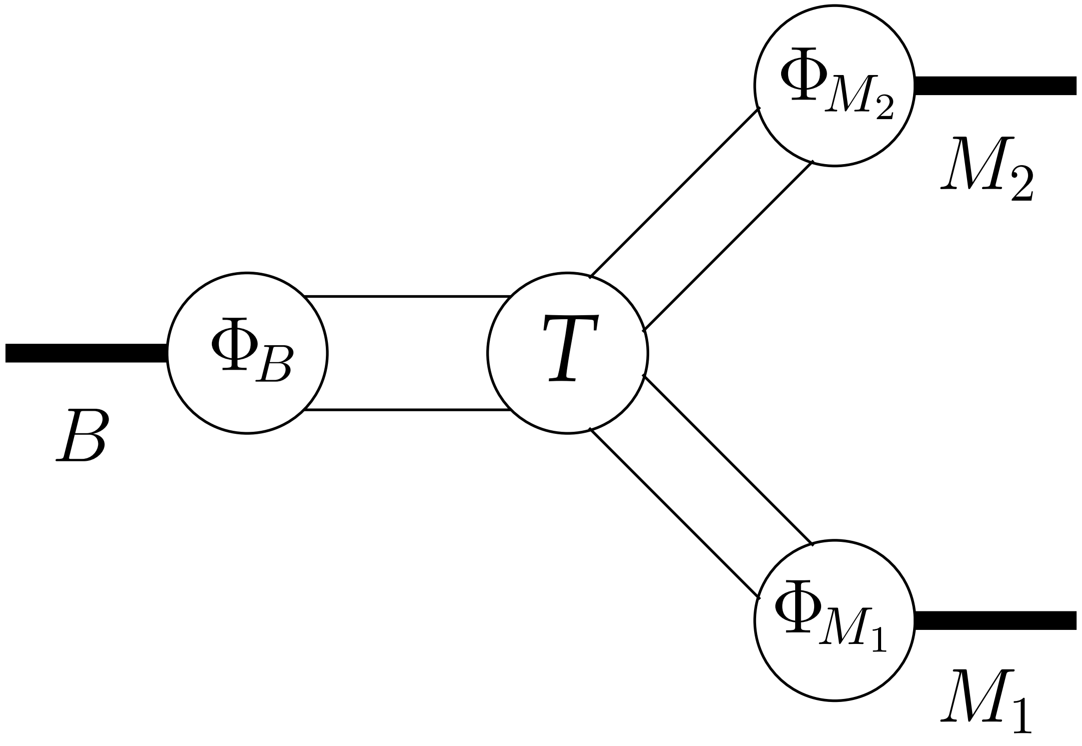


Penguin annihilation (PA)

- Can use isospin and SU(3) to relate different amplitudes.
  - In practice, such analyses often neglect some contributions.

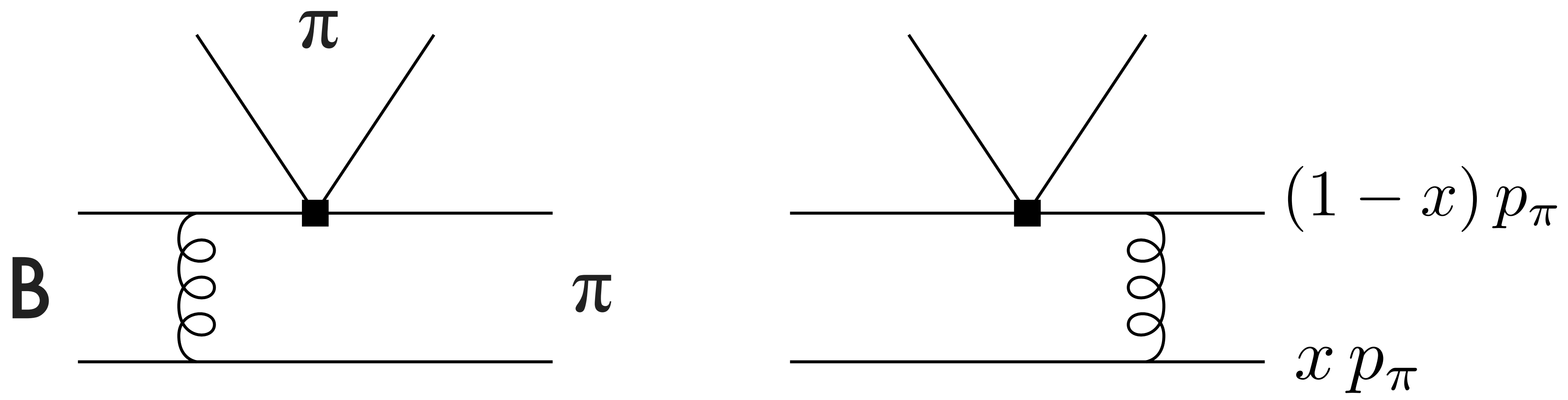
Factorization theorem for B→M_1 M_2

- When factorization theorems for exclusive processes were first discussed around 1980, people were hoping for a factorization theorem of the form:



Factorization theorem for B$\to M_1\, M_2$

- Does not work!



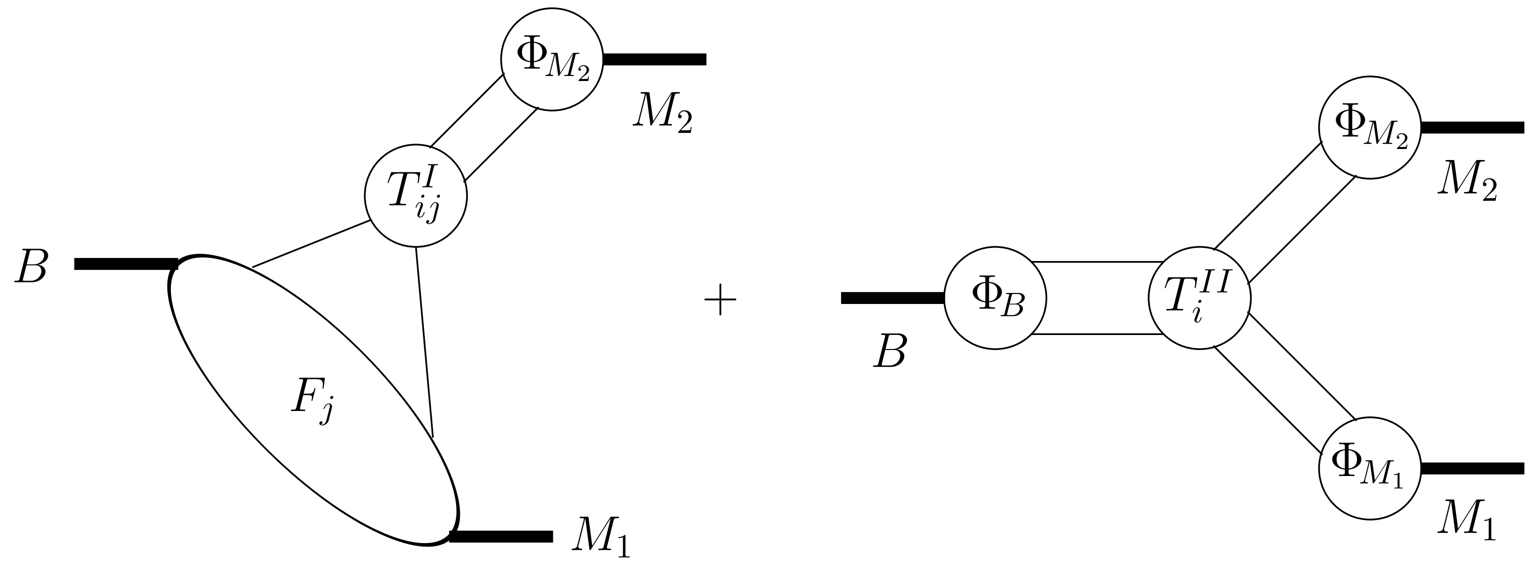
- Kernel T behaves as $T \propto \dfrac{1}{x^2}$ for $x \to 0$
- Pion LCDA goes like $\phi_\pi(x) \propto x$ for $x \to 0$
- Convolution integral does not exist

$$\int_0^1 dx\, T(x)\, \phi_\pi(x) = \infty$$

Factorization theorem by BBNS

Beneke, Buchalla, Neubert, Sachrajda '99

- Give up on complete factorization and allow for a nonfactorizable form factor piece!

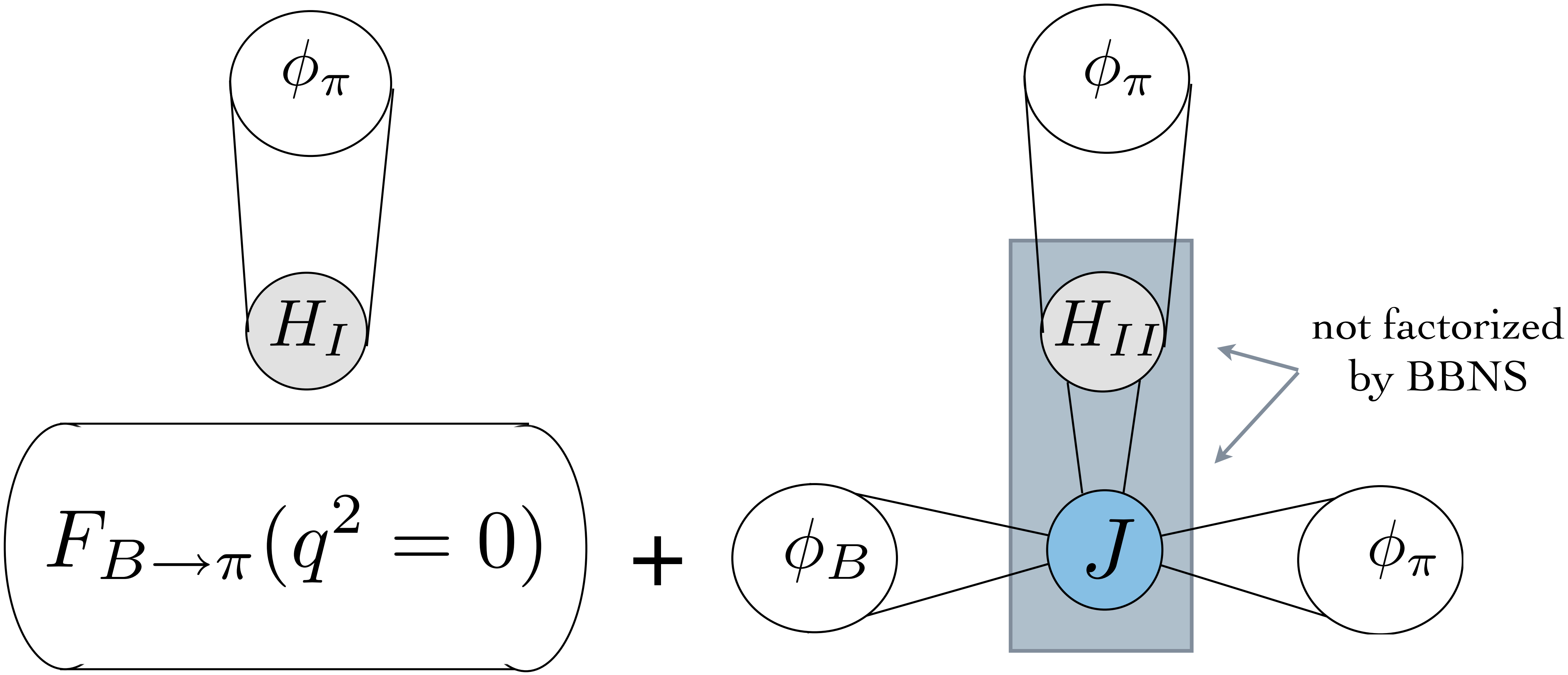


- This works, but the hope for complete factorization is still alive...
  - "pQCD framework": resummation of perturbative corrections to kernel will cure divergence in convolution integral

    Keum, Li, Sanda
  - "Zero-bin subtraction": divergence in convolution is UV. Renormalize it away.

    Manohar and Stewart, hep-ph/0605001

SCET analysis



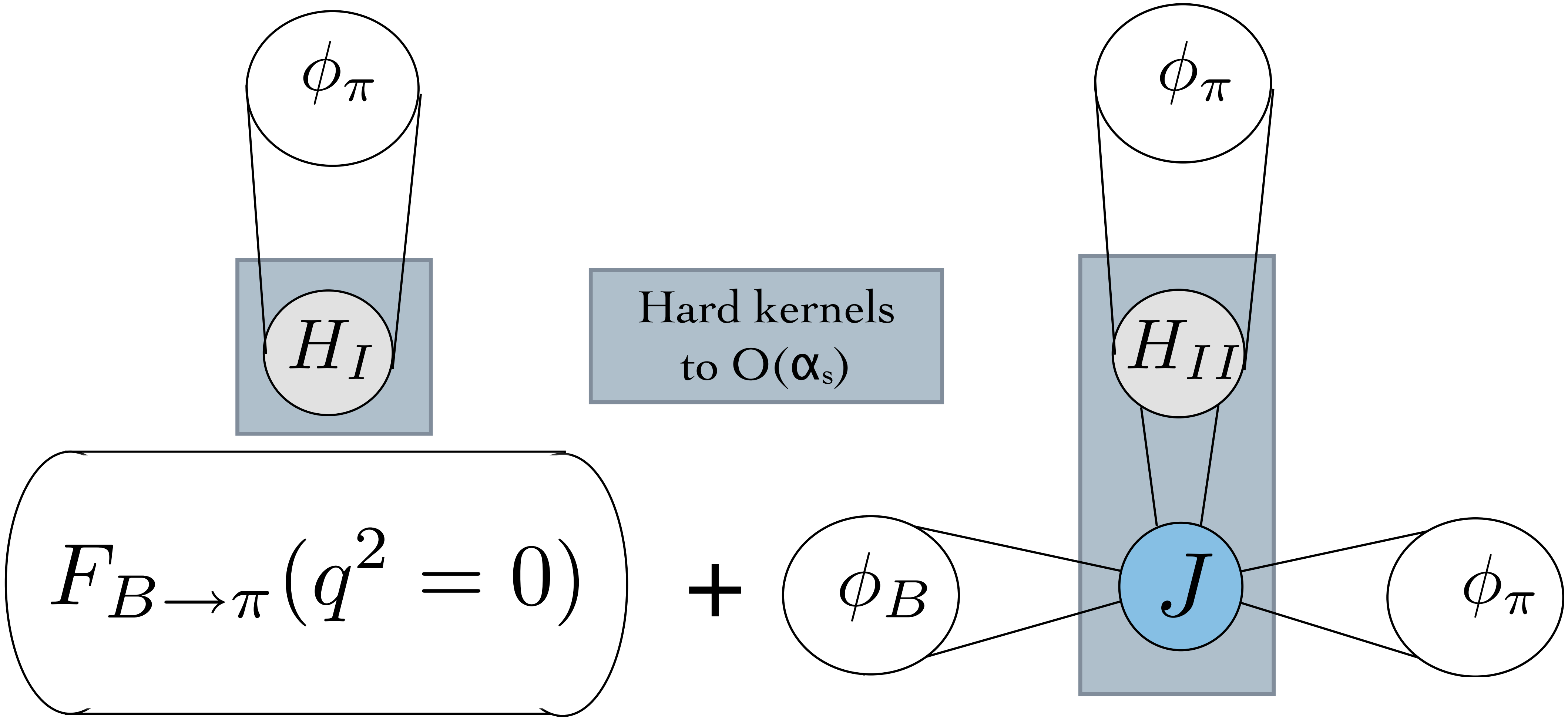
- Same factorization theorem as BBNS.
- $T_I = H_I$. Kernel T_{II} factorizes into hard- and jet-function:

$$H_{II} \equiv H_{II}(\alpha_s(m_b))$$
$$J \equiv J(\alpha_s(\sqrt{m_b \Lambda_{\rm QCD}}))$$

Hadronic input

- Need hadronic input to make predictions:
  - LCDA's for all the mesons
    - Very little is known about light meson LCDAs.
    - Essentially no information on B-meson LCDA
  - Form factors $F_{B\to M}\,(q^2{=}0)$
    - New exp. results on $B\to\pi\, l\, \nu$ give fairly accurate value for $|V_{ub}|\, F_{B\to\pi}\,(0)$
    - other form factors are poorly known.

Phenomenological analysis: BBNS



LCDAs and $F(q^2{=}0)$ from light-cone sum rules

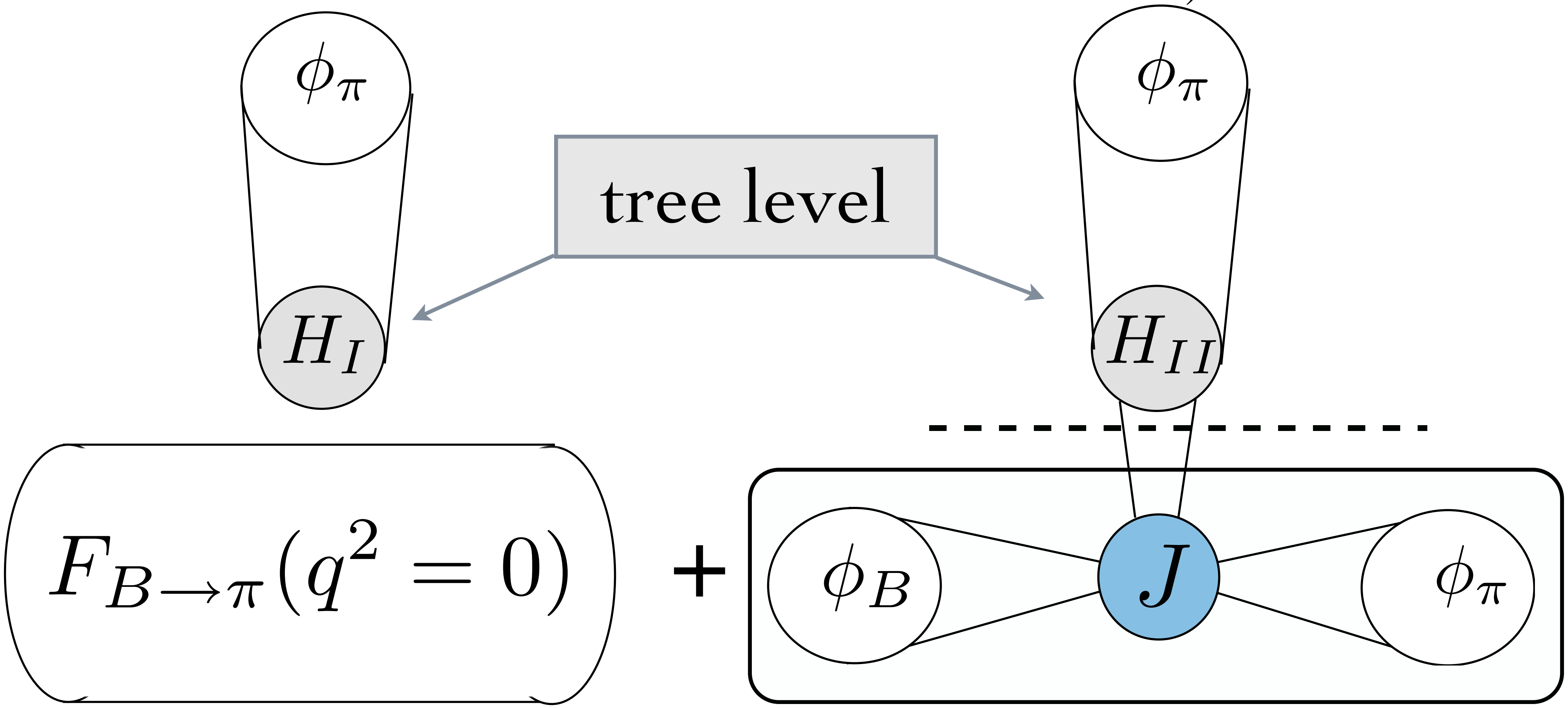
Jet-function $\propto \alpha_s(\mu_i)$

model dependence

Estimate dominant power corrections.

Phenomenological analysis: "SCET approach"

Bauer, Pirjol, Stewart, Rothstein '04



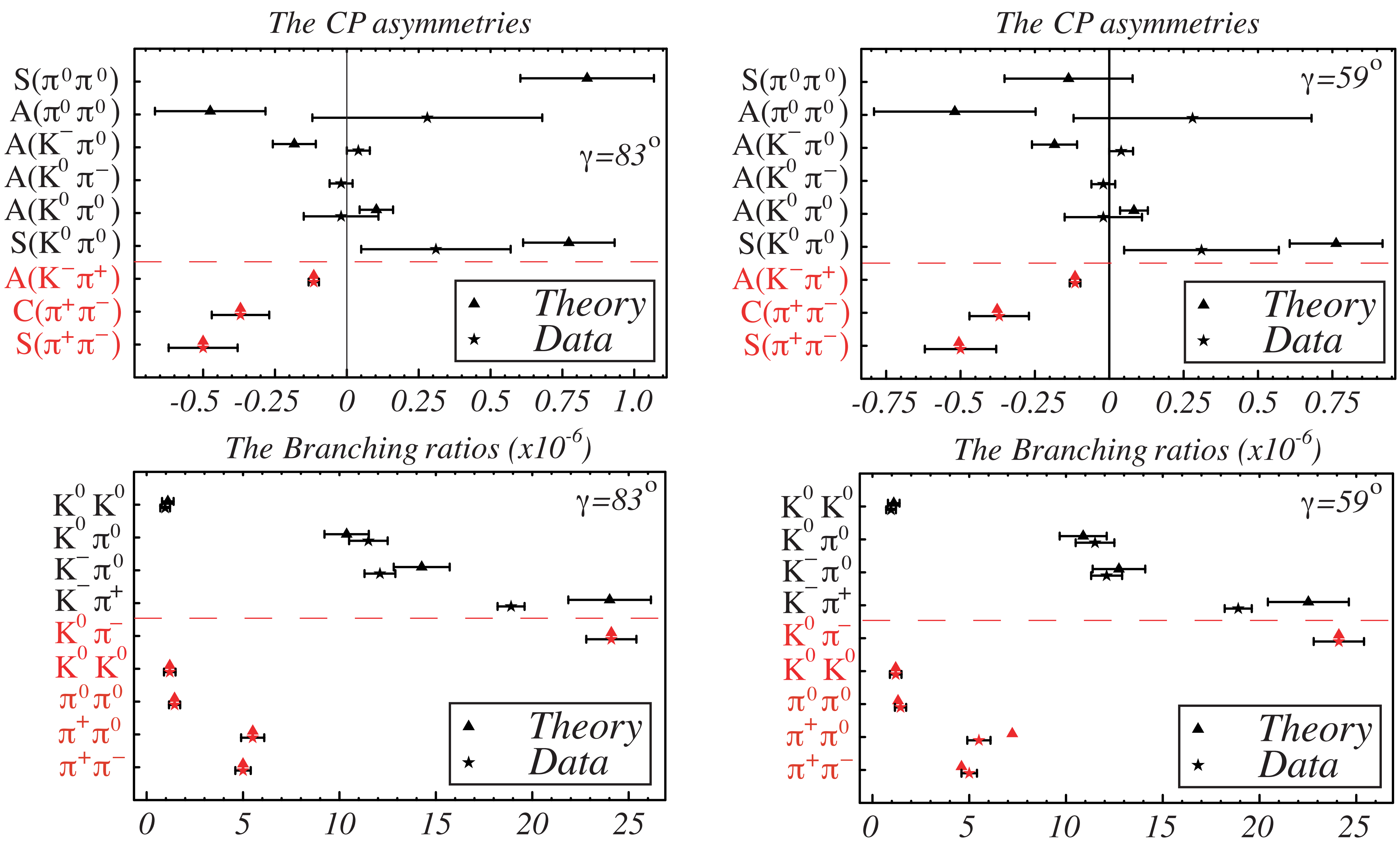
from fit to $B \to \pi\pi$. BPRS find two parts are comparable in size! $\alpha_s(\mu_i)$ suppression?

Leave (charming) penguins unfactorized.
Neglect all power corrections.

Comparison

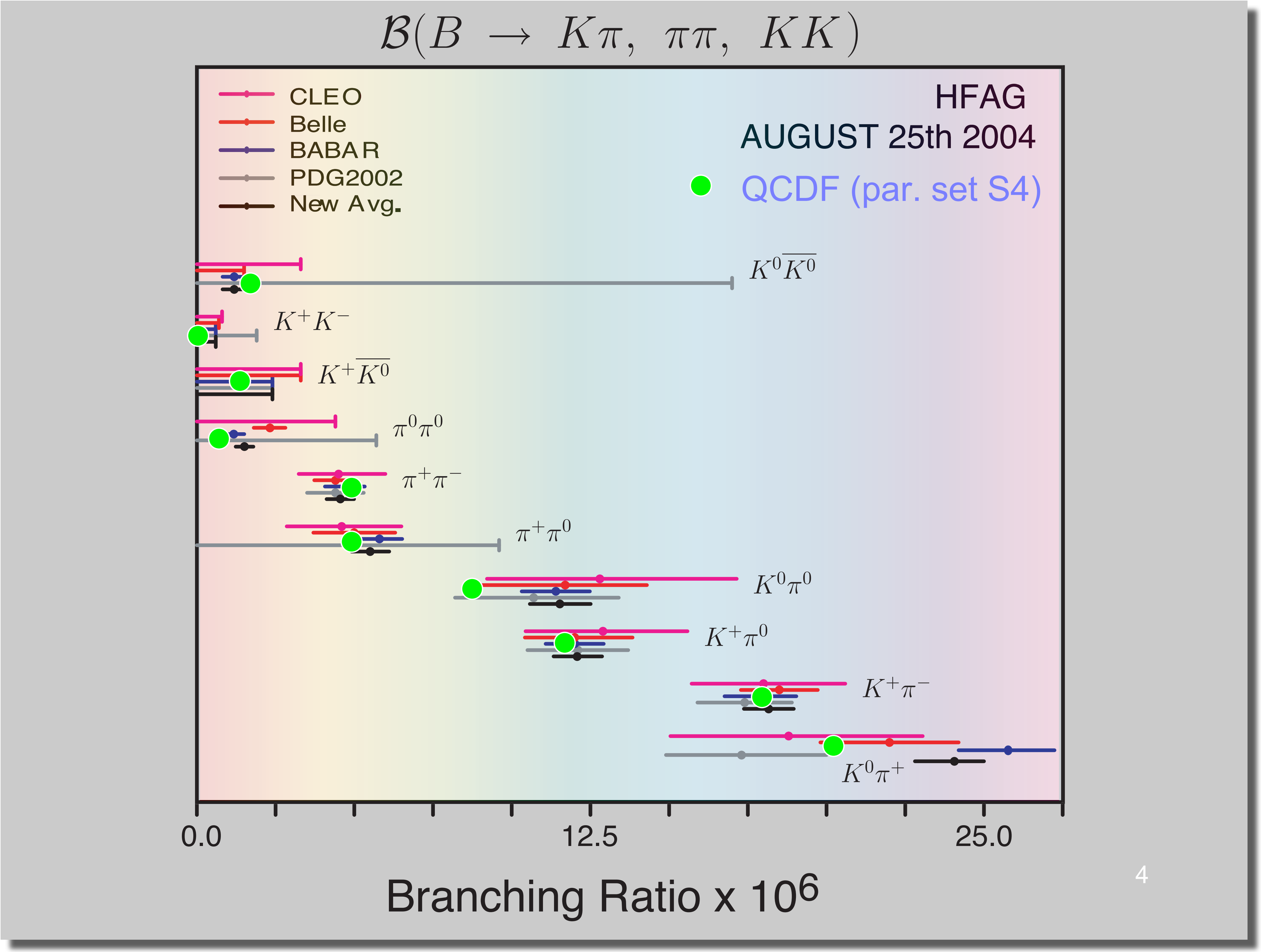
- “SCET approach”:
  - ☑ Model independent; no dependence on light-cone sum rules.
  - ☐ might not be very precise: no power and no perturbative corrections. (BBNS find large power corrections.)
  - ○ More modest/less predictive. Penguins from fit, strong phases from fit, ...

Numerical results: BPRS

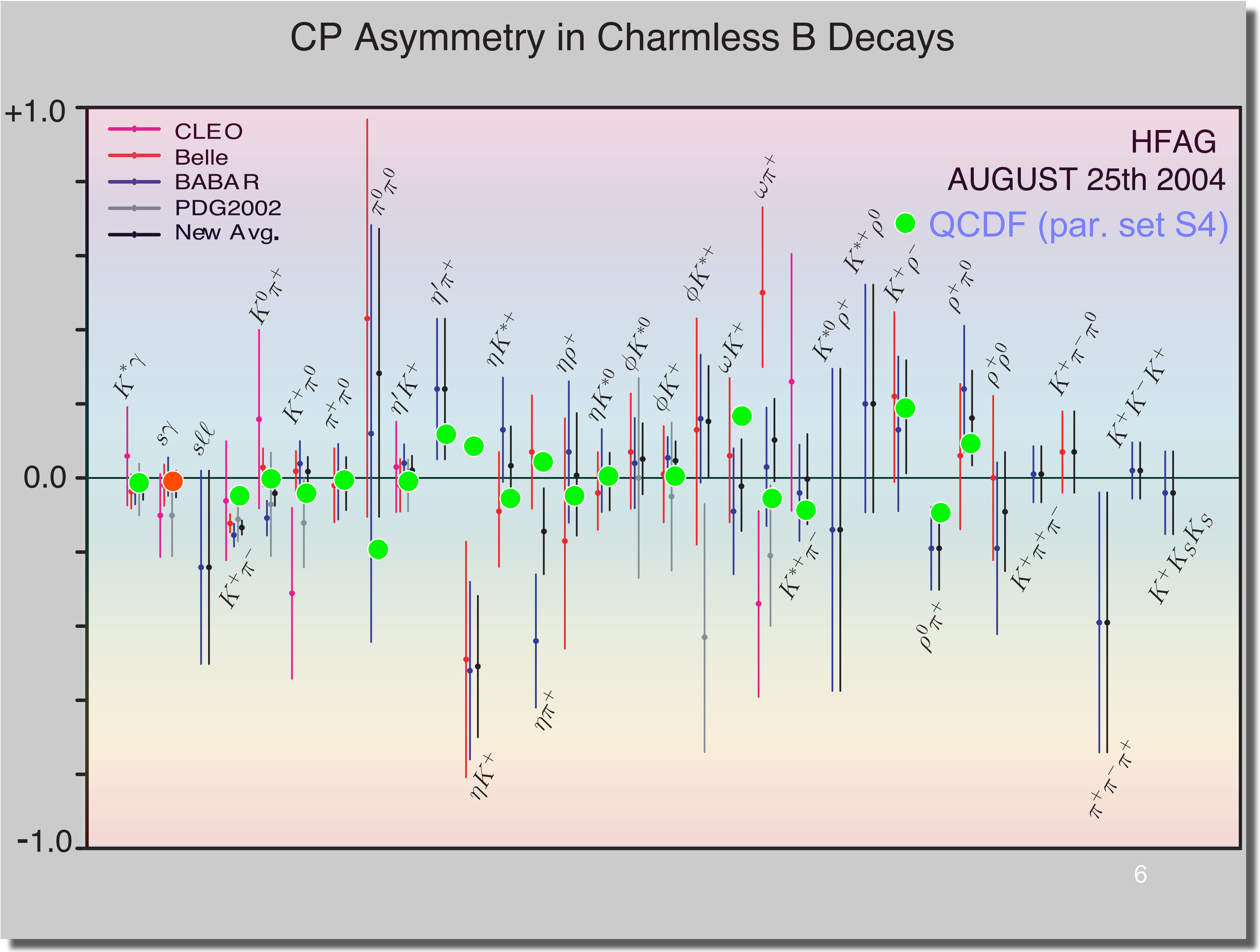


- Red quantities are input.
- Their fit gives two solutions $\gamma=59^o$, 83^o

Numerical results BBNS



CP asymmetries: BBNS



Semileptonic data

- Important difference is relative size of factorizable part and form factor part.
  - BPRS fit gives the two parts are of similar size, but factorizable part is proportional $\alpha_s(\sqrt{m_b\Lambda})$
  - Slope of $B\to\pi$ form factor at $q^2=0$ gives information on relative size.
- Factorization test

$$R = \frac{\Gamma(B^- \to \pi^-\pi^0)}{d\Gamma(\bar{B}^0 \to \pi^+\ell^-\bar{\nu})/dq^2|_{q^2=0}} = 0.76\,^{+0.22}_{-0.18} \pm 0.05\,\mathrm{GeV}^2\,,$$

  - Naive factorization: $R = 0.62 \pm 0.07$
  - BBNS: $R = 0.66^{+0.13}_{-0.08}$
  - BPRS: $R = 1.27^{+0.22}_{-0.29}$

Summary

- Hadronic *B*-decays are a challenge for theory!
- Lots of progress in our understanding, but many basic questions are still open:
  - Relative size of the two parts in factorization formula.
  - Does the $B \to M$ form factor factorize?
  - Hadronic input.
  - Size of power corrections.
  - Charming penguins.
  - ....
- Keep posted!